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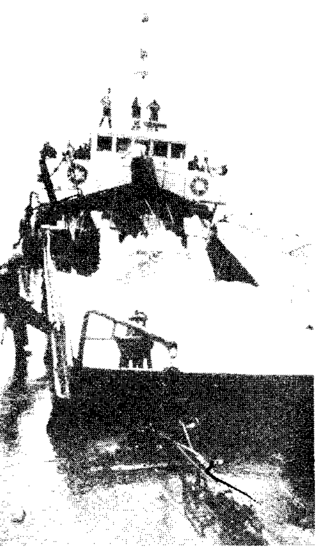

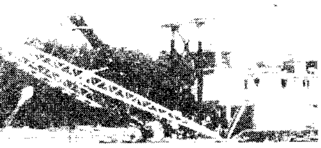

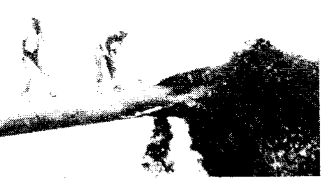

IMPROVEMENT OF OPERATIONS AND MAINTENANCE TECHNIQUES RESEARCH PROGRAM

MISCELLANEOUS PAPER EL-91-20

INNOVATIVE TECHNOLOGIES FOR DREDGING CONTAMINATED SEDIMENTS

by

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13. ABSTRACT *(Maximum 200 words)*

Contaminated marine sediments exist in many US waterways. Dredging is often a convenient and economical method of safely removing these sediments. However, significant concern exists over the potential environmental effects resulting from the localized sediment resuspension and contaminant release that may occur during the removal operation. This report synopsizes hydraulic, pneumatic, and mechanical dredging innovations and discusses their application to dredging of contaminated sediments.

14. SUBJECT TERMS

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Dredging	Hydraulic dredges	Pneumatic dredges
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Preface

The study reported herein was conducted by the Environmental Laboratory (EL) of the US Army Engineer Waterways Experiment Station (WES), as part of the Improvement of Operations and Maintenance Techniques (IOMT) Research Program, Work Unit 32569.

The report was prepared by Mr. Paul A. Zappi and Dr. Donald F. Hayes of the Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), EL. Mr. Daniel E. Averett, Water Supply and Waste Treatment Group, EED, EL, and Dr. Michael R. Palermo, Research Projects Group, EED, EL, provided technical review. The IOMT Program Manager was Mr. Robert F. Athow, Estuaries Division, Hydraulics Laboratory, WES.

This study was conducted under the direct supervision of Dr. John J. Ingram, Chief, WREG, and under the general supervision of Dr. Raymond L. Montgomery, Chief, EED, and Dr. John Harrison, Chief, EL.

Commander and Director of WES was COL Larry B. Fulton, EN. Dr. Robert W. Whalin was Technical Director.

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Conversion Factors, Non-SI to SI Units Of Measurement

Non-SI units of measure used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	2.54	centimeters
knots (international)	0.5244444	meters per second
miles (US statute)	1.609347	kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

Background

Sediment contamination resulting from agricultural and industrial sources exists in many harbors, ports, and navigable streams. While only a small portion of the sediment dredged by the US Army Corps of Engineers (USACE) for navigation projects is contaminated, these and other contaminated sediments require environmentally sound removal techniques. This report provides a synopsis of research efforts associated with innovative hydraulic, pneumatic, and mechanical technologies for dredging contaminated sediments.

The affinity of most contaminants for fine sediment particles presents an interesting dichotomy. This affinity causes the movement of fine particles to mirror the potential for contaminant spread; thus, suspended sediment can be used as a convenient tracer for contaminant transport. Unfortunately, the slow settling velocities of fine particles increase the likelihood of contaminant transport away from the dredging site. Therefore, minimizing sediment resuspension is an important aspect of dredging contaminated sediments and should be considered in selecting dredging methods and equipment.

While no simple criteria exist for safe levels of sediment resuspension, less sediment resuspension results in less potential for contaminant transport and subsequent release to the environment.

Loosely bound contaminants may be released to the environment as a result of the energy induced during the dredging process. This energy may strip contaminants bound to sediment particles and cause them to disperse into the water column. However, most contaminants are tightly bound and are unlikely to be stripped from the sediment particles. The potential for such releases depends upon many factors, including sediment characteristics, contaminants present, and local environmental conditions.

Based upon the above rationale, this report focuses on sediment resuspension potential during the dredging process. Site and dredge characteristics for resuspension studies at various locations are summarized based

based upon available information. The site-specific nature and limited data preclude in-depth comparisons between dredge types and should temper any later comparisons based upon this report. However, this report should give the reader insight into available innovative dredging equipment and the potential for sediment resuspension during the dredging process.

Additionally, other factors such as physical characteristics of the dredging area (depth, sediment quantity, access, traffic, etc.), sediment physical and chemical characteristics, disposal techniques, equipment availability, and economics should be considered when selecting a dredge to remove contaminated sediments. These factors often dictate the dredge types open to consideration.

Previous research has shown the importance of proper dredge operation in minimizing sediment resuspension. Selection of dredging equipment or development of a dredging plan must include operational considerations as a critical component. Since such operational considerations could potentially inhibit dredge production, encouraging environmentally sound practices in contracted dredging work may be one of the more challenging aspects of dredging contaminated sediments.

Another topic of concern is the importation of equipment from other countries. The Jones Act (46 CFR 292) strictly prohibits the importation of foreign-built ship hulls into the United States. While it was established to protect the US shipbuilding industry from foreign shipbuilders, the Jones Act has also restricted the importation of foreign built dredges. Although not clear, this act may not prevent the importation of dredgeheads (Mitre Corporation 1983).

Purpose and Scope

This report synopsizes hydraulic, pneumatic, and mechanical dredges and innovative modifications to their dredgeheads. It also examines previously tested dredging equipment designed to remove fine-grained sediments with a minimum amount of sediment resuspension. Major features of equipment innovations, along with available field testing information, are discussed. From these findings, the most promising innovations and research needs are identified.

Since this report focuses on the dredging operation, only dredge sizes and sediment resuspension quantities are reported. Information useful in the selection of a dredge based on the disposal method can be found in the cited references.

It is worthy to note that some references used in preparing this report formed a relationship between turbidity and suspended solids and refer to turbidity in parts per million or milligrams per liter. This provides some confusion in the data since turbidity is a measure of light scatter or passage and cannot have concentration units. From all indications, values reported in concentration units (ppm or mg/L) are either measured or calculated suspended solids values errantly referred to as turbidity.

Yagi, Koiwa, and Miyazaki (1976) presented a correlation between turbidity (in ppm) and suspended solids (in mg/L), which further verifies this reasoning. Where possible and applicable, correlations between turbidity and suspended solids are presented. Unfortunately, many reports did not contain site-specific correlations, which severely limits the usefulness of the data.

Additionally, most cited references did not specifically state whether the reported suspended solids values included background concentrations. Suspended solids concentrations reported as above background are so noted.

2 Hydraulic Dredging Equipment

Dredges that move sediment via hydraulic means routinely operate in almost every waterway in the United States and move millions of cubic yards of sediment each year. These dredges use various types of dredgehead and pump configurations to facilitate the initial gathering of bottom sediment and to move sediments in a slurry form. Commonly used hydraulic dredges include the cutterhead, dustpan, bucket wheel, and hopper dredges.

Hydraulic dredges are generally efficient sediment movers and resuspend less sediment than previously thought (McLellan et al. 1989). Thus, they provide an economical means for removing large quantities of contaminated sediments. Also, further reductions in sediment resuspension potential are possible with proper operational controls (Hayes, McLellan, and Truitt 1988). Many dredgehead variations exist, some of which have been developed specifically to reduce resuspension at the point of dredging. This section discusses hydraulic dredges, operational considerations, and dredgehead designs that may reduce sediment resuspension during dredging.

Cutterhead Dredges

Conventional cutterhead dredges (Figure 1) are the most common hydraulic dredges in the United States. The combination of mechanical and hydraulic systems makes the cutterhead one of the most versatile and efficient dredging systems. Cutterhead dredges are generally classified by the size of their discharge pipe diameter, with common sizes ranging from 6 to 36 in.[1] and an equivalent range of pump sizes.

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page xi.

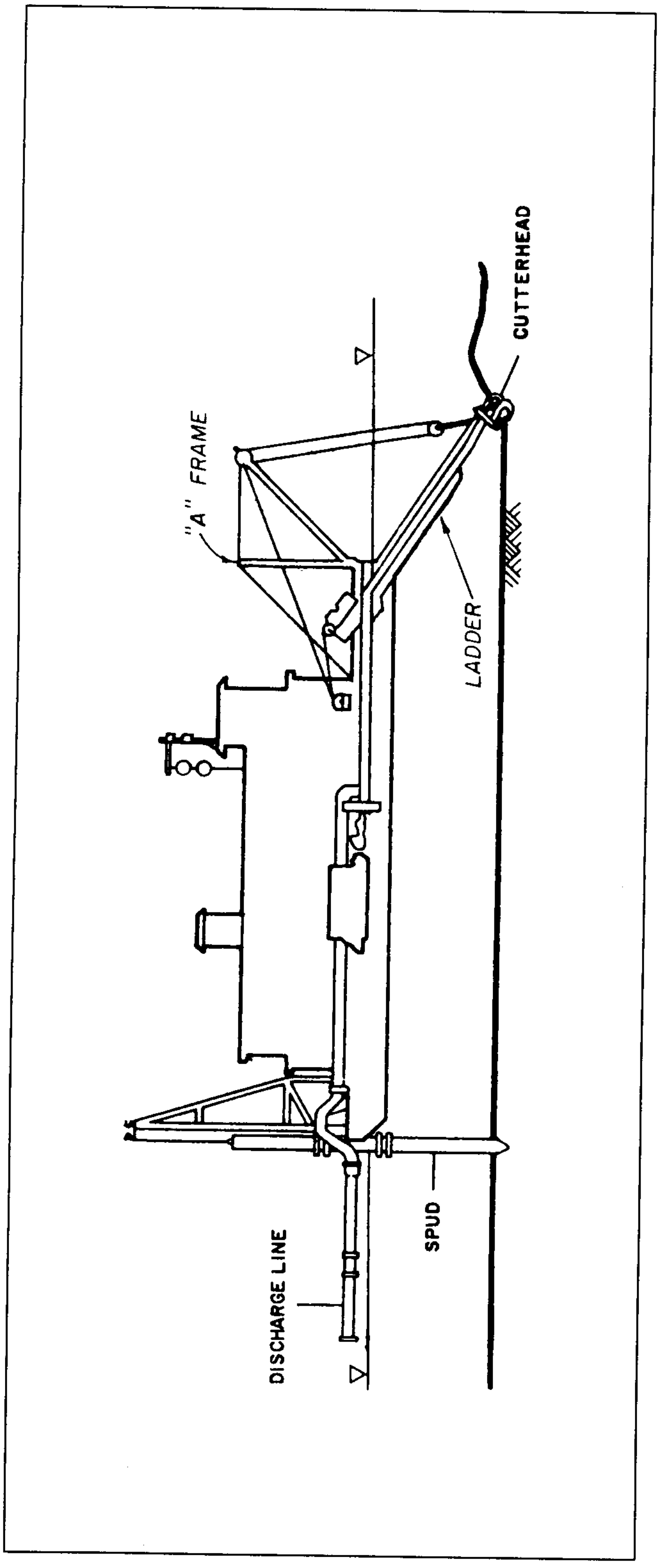

Figure 1. Cutterhead dredge (from McLellan et al. 1989)

The cutterhead uses a rotating cutter to dislodge sediment and guide it into a suction inlet (Figure 2). Once the material enters the suction inlet, it is pumped through a pipeline to its point of discharge or disposal.

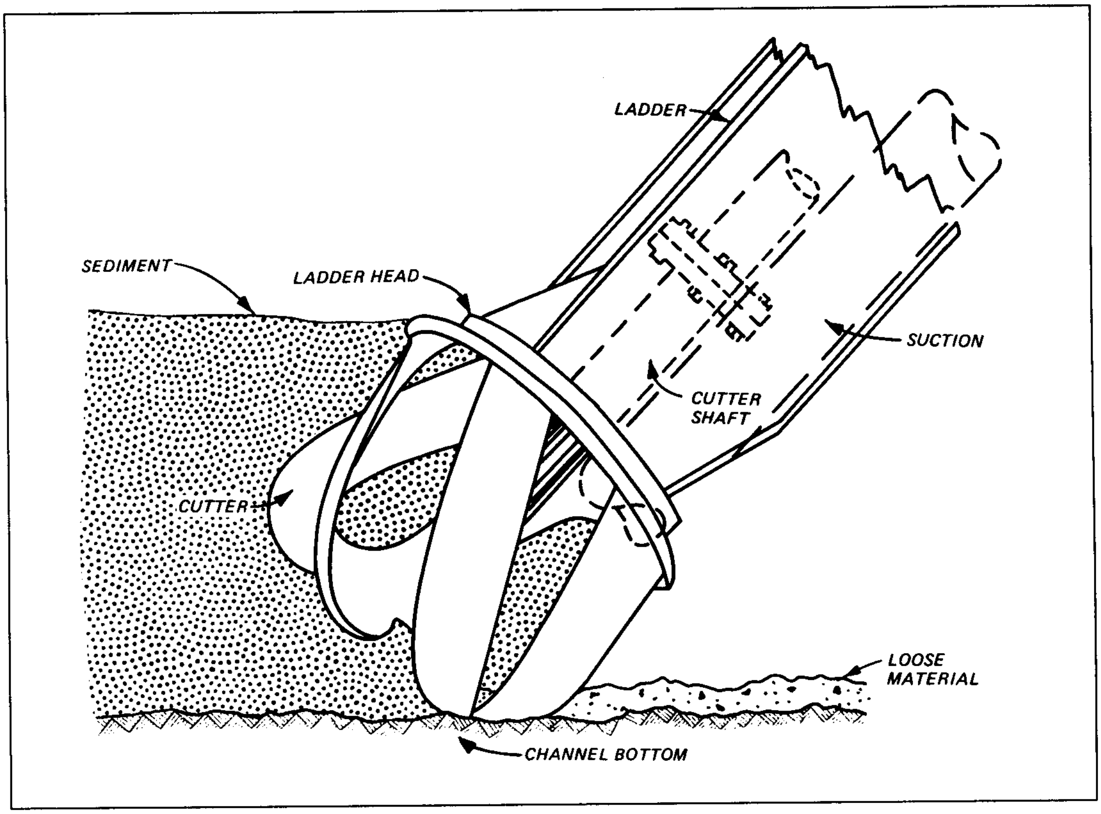

Figure 2. Conventional cutterhead (modified from Huston and Huston 1976)

The amount of sediment resuspended by cutterhead dredges depends upon many variables, including dredge movement, cutter penetration, and cutter rotation speed. The dynamics of cutter rotation have led to a general perception that cutterhead dredges resuspend large quantities of sediment because of a violent mixing action. Recent research, however, has proven this perception to be largely unfounded (Hayes, McLellan, and Truitt 1988).

Cutterhead dredges generally resuspend sediment in the lower portion of the water column and in the immediate vicinity of the cutterhead. With proper operational controls, the concentration of suspended solids around a conventional cutterhead dredge ranges from 5 to 200 mg/L (McLellan et al. 1989).

Modifications to conventional cutterhead dredges that may help reduce sediment resuspension include the following: shielded cutters, alternate cutter designs (e.g., Clean-Up and Refresher), cutterless dredgeheads, bottom sensors, gas collection systems, and underwater cameras. Innovative designs include the Clean-Up, Matchbox, Refresher, and modified dustpan dredgeheads.

Clean-Up dredge

The Clean-Up dredge was designed by TOA Harbor Works[2] to remove highly contaminated sediments (Figure 3). Six Clean-Up dredges

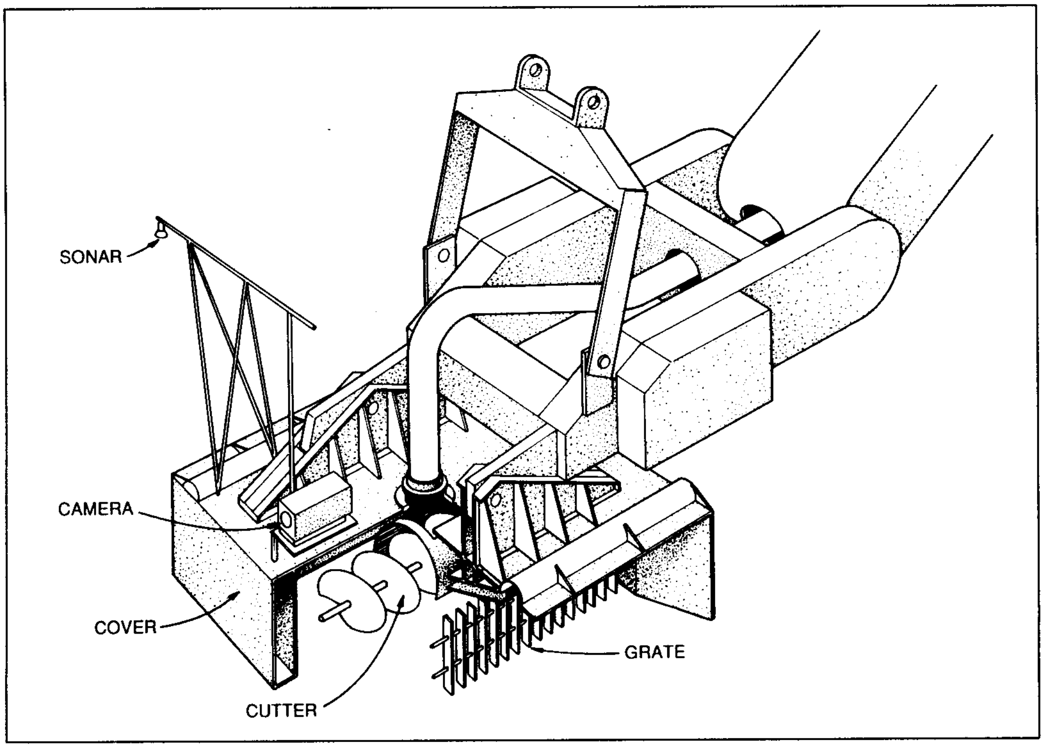

Figure 3. Clean-Up dredgehead (from Sato 1982)

(Nos. 1-5 and Clean-Up SIRSI) currently operate in Japan. Clean-Up dredges Nos. 1-5 are equipped with centrifugal pumps, while the Clean-Up SIRSI is equipped with a 300/60 Pneuma pump (Barnard 1978; Sato 1976, 1984). (The Pneuma pump is discussed in more detail in Chapter 3.) Features of the Clean-Up dredge include:

a. *Auger cutter*. Rotates perpendicular to the suction pipe axis, functions as a mixing device to provide a slurry of uniform density

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2 TOA Kensetsu Kogyo Company, Ltd., 5 Yobancho, Chiyoda-ku, Tokyo, Japan.

and viscosity to the pump, and provides smooth movement of the slurry to the suction mouth.

b. *Rectangular cover.* Located over the cutter with movable shutters, intercepts the release of resuspended sediment, and prevents the inflow of excess water.

c. *Sonar.* Monitors the elevation in front and back of the dredgehead and keeps its position horizontal regardless of depth.

d. *Grates.* Prevent large objects from clogging the suction intake.

When needed, an underwater camera and gas collection system can be added to the dredgehead. Underwater cameras monitor sediment resuspension, and gas collection systems collect sediment-entrained gas that is released during movement of the dredgehead through the sediment.

Sato (1976) summarized the work of Clean-Up No. 2 operating in a silty clay sediment at an unreported water depth. Suspended solids concentrations measured during this test are reported in Table 1. Background suspended solids at this site ranged from 5 to 9 mg/L. Sato (1984) reported that, as of the end of 1981, the Clean-Up dredge had been used at 45 separate dredging projects, primarily in soft mud and sand.

Under normal bottom conditions, the maximum suspended solids concentration around a Clean-Up dredge ranges from 6 to 8 mg/L; however, the suspended solids sometimes increases to 80 to 100 mg/L during starting and stopping of the pump or changes in swing directions (Sato 1984).

Matchbox dredge

Volker Stevin Dredging Company of The Netherlands developed the Matchbox dredge (Figure 4) to remove highly contaminated sediments in the First Petroleum Harbor, The Netherlands.

Features of the Matchbox dredge include:

a. *Triangular cover.* Contains sediment-entrained gas and prevents the inflow of excess water into the suction system.

b. *Funnel intakes.* Side openings that guide sediment toward the suction intake as the dredge swings. Valves to open and close the side opening opposite the direction of swing help avoid the inflow of excess water.

c. *Angle control.* Hydraulic pistons adjust the angle between the dredgehead and ladder to ensure that the dredgehead remains parallel to the bottom regardless of dredging depth.

Table 1
Clean-Up Dredge Field Test (Sato 1982)

Location	Suspended Solids Concentration (mg/L)					
	Near-Field (≤3 m of Dredgehead)					
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Water Surface	2.3	3.3	1.7	2.2	3.0	1.9
3-m depth	4.9	2.1	2.1	7.0	4.0	1.1
	Far-Field					
75 m north of dredging area						
Water surface	1.6					
3-m depth	2.3					
75 m north and east of dredging area						
Water surface	2.5					
3-m depth	2.3					
25 m north of dredging area						
Water surface	1.8					
3-m depth	4.0					
25 m north and 75 m east of dredging area						
Water surface	2.3					
3-m depth	2.8					
At dredgehead						
Water surface	3.0					
3-m depth	2.7					

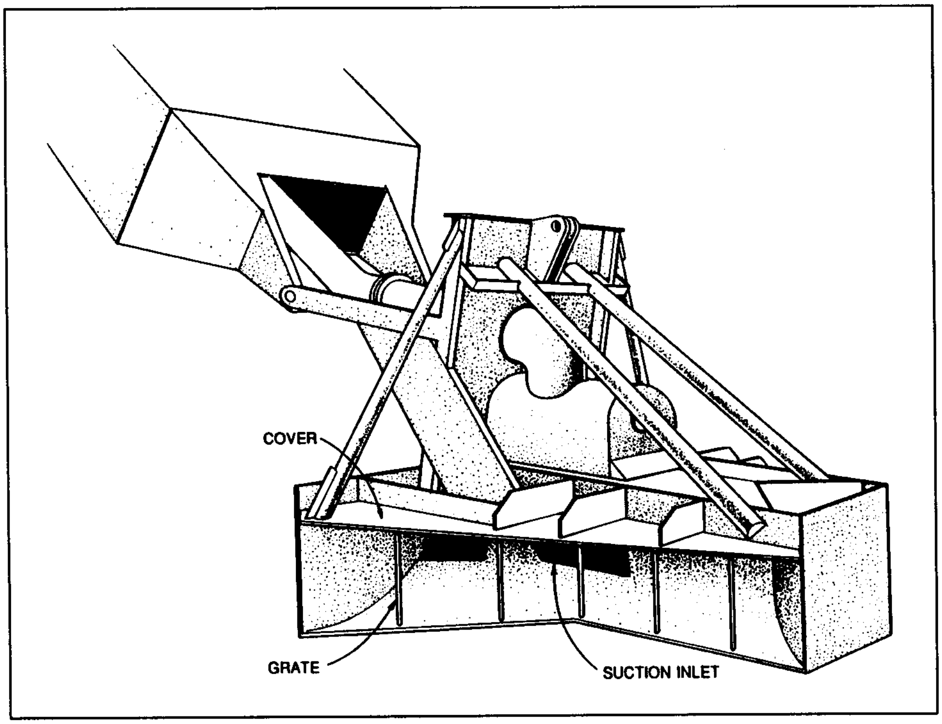

Figure 4. Matchbox dredgehead

d. Vertical positioning. Indicates the depth of the dredgehead relative to the bottom.

e. Grates. Prevent large objects from clogging the suction intake.

Sediment resuspension associated with the Matchbox dredge has been monitored for the First Petroleum Harbor and for Calumet and New Bedford Harbors in the United States. Brief descriptions of these field tests and the performance of the Matchbox dredgehead follow.

First Petroleum Harbor. Between December 1981 and December 1983, contaminated sediments were removed from the First Petroleum Harbor on the River Nieuwe Maas, The Netherlands, using a Matchbox dredge. Sediment in the harbor was a heavily polluted silt that contained high concentrations of pesticides and chlorinated hydrocarbons. Water depths in this area ranged from 5 to 12 m. The traditional cutterhead was replaced with a Matchbox dredgehead on the 650-mm hydraulic dredge *Otter*, owned by Volker Stevin Dredging Company (d'Angremond, de Jong, and de Waard 1984).

The suspended solids concentrations around the dredgehead and the background concentrations were estimated from graphs provided by d'Angremond, de Jong, and de Waard (1984). Suspended solids at a distance of 2 to 5 m from the suction head during dredging were approximately 12 mg/L from the water surface to a depth of 7 m, and varied almost linearly from 12 to 80 mg/L from a depth of 7 to 11 m. Background suspended solids near the dredge were less than 25 mg/L from the water surface to a depth of approximately 9 m, and varied almost linearly from 25 to 60 mg/L from a depth of 9 to 12.5 m.

Calumet Harbor. In October 1985, the US Army Engineer Waterways Experiment Station (WES) and the US Army Engineer District (USAED), Chicago, monitored the sediment resuspension characteristics of the 12-in. cutterhead dredge *Dubuque* of the USAED, St. Paul, fitted with a Matchbox dredgehead. The Matchbox dredgehead was designed for the *Dubuque* by Volker Stevin Dredging Company, The Netherlands, and by Bean Dredging Company of New Orleans, LA, and was purchased by the USAED, Chicago. The Matchbox dredgehead was equipped with the design features described previously, with the exception of vertical positioning instrumentation.

The sediment resuspension tests were conducted in Calumet Harbor, Illinois, located south of Chicago, on the western shore of Lake Michigan. The sediment dredged was a silty loam with a Unified Soil Classification System (USCS) classification of ML. The initial water depth at this site was approximately 8 m (McLellan, Truitt, and Palermo 1986; Hayes, McLellan, and Truitt 1988; McLellan et al. 1989).

Average suspended solids concentrations at the dredgehead and at locations of 15, 31, 61, 122, and 244 m from the dredgehead are reported in Table 2. While clogging of the suction intake and inexperience of the operator may have affected the Matchbox performance, no suspended solids plume at two times background was noted for the Matchbox dredge at 5-, 50-, and 80-percent depths; however, there was a plume of 10.5 acres at 95-percent depth. Background suspended solids ranged from 2 to 5 mg/L and averaged 4 mg/L.

Table 2
Calumet Harbor Matchbox Dredge Field Test (Hayes 1986)

Percent Depth	Average Suspended Solids (mg/L)					
	At Matchbox	15 m from Matchbox	31 m from Matchbox	61 m from Matchbox	122 m from Matchbox	244 m from Matchbox
5	—	3	2	3	3	3
50	—	4	4	4	4	3
80	19[1]	8	5	12	8	10
95	—	12	13	31	8	9

[1] Above background.

Additional details of sediment resuspension associated with the Matchbox and cutterhead dredgeheads tested in Calumet Harbor are available in Hayes, McLellan, and Truitt (1988).

New Bedford Harbor. From November 1988 to February 1989, the WES, the US Army Engineer Division, New England, and the US Environmental Protection Agency (USEPA) conducted a pilot study in New Bedford Harbor, Massachusetts, to test the effectiveness of the Matchbox dredgehead. New Bedford Harbor is an estuary of the Acushnet River that separates the cities of New Bedford and Fairhaven, MA. Sediment at the New Bedford Harbor site consisted of organic silts and clays contaminated with polychlorinated biphenyls (PCBs) and heavy metals. Water depths ranged from 0.3 to 1.8 m.

Bean Dredging designed, built, and installed the Matchbox dredgehead on one of their 12-in. cutterless dredges. Water jets were designed to unclog the Matchbox's suction intake; however, these were not used since they could increase suspended sediment in the water column (Otis 1990; Otis, Andon, and Bellmer 1990).

Resuspension rates and contaminant release at the point of dredging varied, but suspended sediment and contaminant concentrations generally returned to background levels within 150 m. The Matchbox dredge had an average resuspension rate of 46 g/sec at the dredgehead. Suspended solids concentrations at approximately 60, 120, and 180 m downstream of the dredge, at ebb tide, are reported in Table 3.

Table 3
New Bedford Matchbox Dredge Field Test (Otis, Andon, and Bellmer 1990)

Day	Average Daily Suspended Solids at Middepth (mg/L)			
	At Dredgehead	60 m Downstream of Dredging Area	120 m Downstream of Dredging Area	180 m Downstream of Dredging Area
1	79	8	16	10
2	73	30	13	—
3	609	—	—	—
4	276	—	—	—
5	342	—	—	—
6	262	—	—	—
7	305	—	—	—

Note: Distances are approximate.

The Matchbox dredgehead experienced significant clogging problems due to debris within the bay. Additional details of sediment resuspension associated with the Matchbox and a cutterhead and horizontal auger dredge tested at New Bedford Harbor are available in Otis, Andon, and Bellmer (1990).

Refresher dredge

Penta Ocean Construction Company, Ltd., of Japan developed the Refresher dredge (Figure 5). Dredges of this design currently in operation in Japan include the Refresher No. 6 (Fuyo), the Refresher No. 3, and the Mini-Refresher (Tokyo Maru). The Fuyo and Refresher No. 3 are suitable for large- to medium-scale dredging projects, and the Tokyo Maru is a portable dredge suitable for small-scale projects in narrow areas (Kaneko and Watari 1983; Kaneko, Watari, and Aritomi 1984). Major features of the Refresher dredge include:

a. Helical cutter. Cuts and guides material into the suction intake.

b. Cover. Conceals the cutterhead and prevents the loss of sediment. An adjustable hydraulic shutter opens or shuts the cover as the dredge swings.

c. Positioning equipment. Horizontal and vertical positioning equipment keeps the cutterhead parallel to the bottom with varying dredging depths.

d. Check valves. Located at the suction and discharge side of the pump to prevent the backflow of the sediment into the discharge pipes during an emergency.

An underwater camera, turbidimeter, and gas collection system can be added to the dredgehead when needed. Underwater cameras and turbidimeters monitor sediment resuspension, and gas collection systems collect sediment-entrained gas released during movement of the dredgehead through the sediment.

Sediment resuspension associated with the Refresher dredge has been monitored at T- and M-Bays in Japan. Descriptions of these field tests and the performance of the Refresher's dredgehead are given below.

T-Bay. Between December 1976 and March 1977, material was removed from T-Bay, Japan, by the Refresher No. 6 (Fuyo). The material dredged was primarily silt, in water depths ranging from 7 to 9 ft (Kaneko, Watari, and Aritomi 1984).

Kaneko, Watari, and Aritomi (1984) reported the suspended solid concentrations at this site to be about 1.5 times the turbidity measurement. Calculated suspended solids concentrations at the dredgehead associated with swing speeds of 5 and 10 m/min are provided in Table 4. Background suspended solids varied from approximately 1 to 6 mg/L.

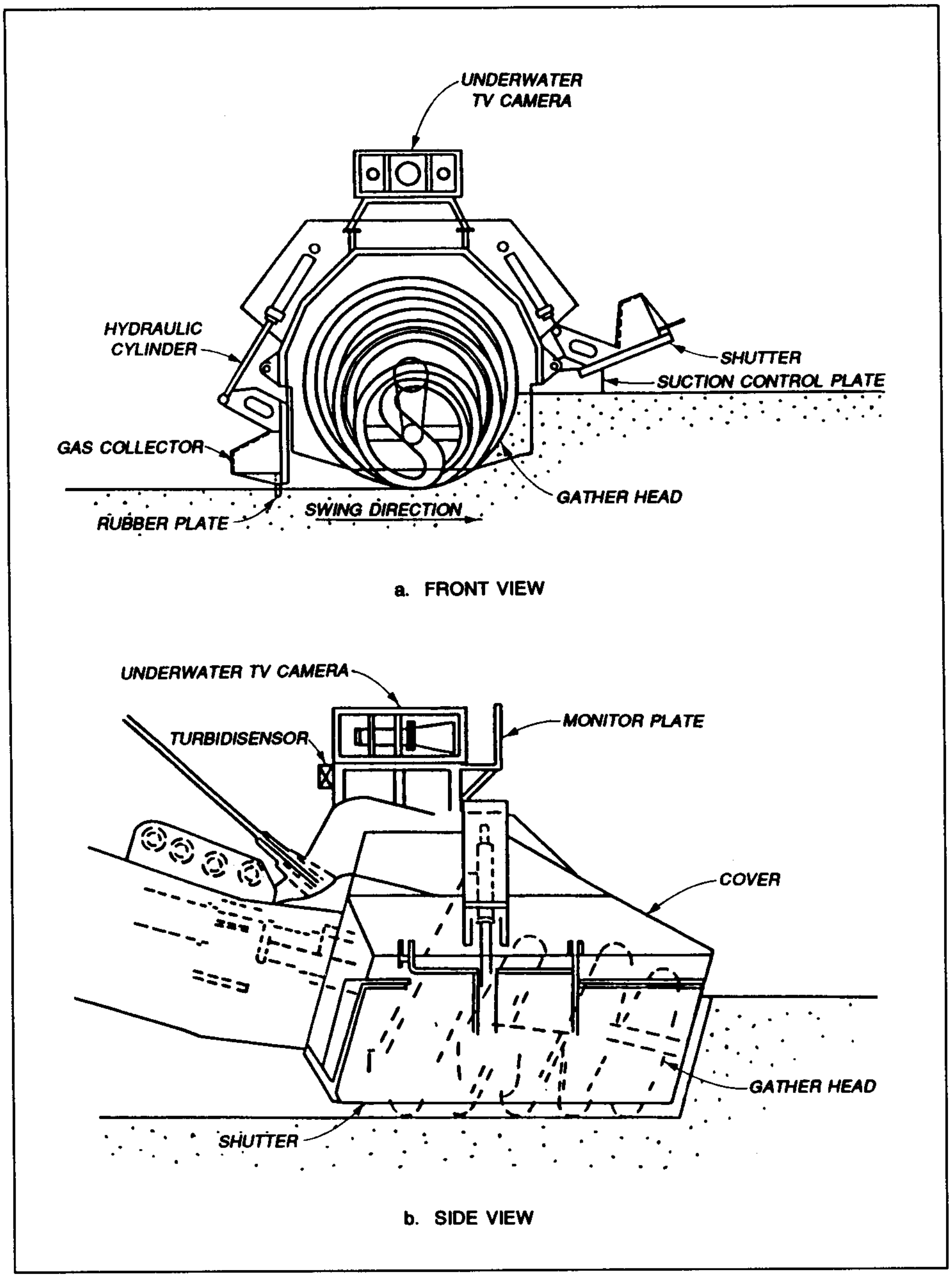

Figure 5. Refresher dredgehead (from Raymond 1984)

Table 4
T-Bay Refresher Dredge Field Test (Kaneko, Watari, and Aritomi 1984)

Swing Speed (m/min)	Suspended Solids (mg/L)	Turbid Area (sq m)
5	4.5	14
10	23.3	17.5

Suspended solids within 50 m of the dredge were estimated from graphs provided by Kaneko, Watari, and Aritomi 1984). Suspended solids varied from approximately 3 to 5 mg/L at depths of 0.5 and 2.0 m, and from approximately 5 to 6 mg/L at 5.0 m.

M-Bay. During 1980 and 1981, Refresher No. 3 removed material from M-Bay, Japan. The sediment was a mix of silt, clay, and colloidal material in water depths ranging from 14 to 15 m. Kaneko, Watari, and Aritomi (1984) reported a suspended solids (SS)-turbidity relationship of

$$SS = 1.17 \times NTU + 3.5$$

where the SS concentration is expressed in milligrams per liter and turbidity is measured as nephelometric turbidity units (NTUs).

Calculated SS concentrations at the dredgehead associated with swing speeds of 4 and 8 m/min are provided in Table 5. Background SS concentrations ranged from approximately 6 to 9 mg/L.

Table 5
M-Bay Refresher Dredge Field Test (Kaneko, Watari, and Aritomi 1984)

Swing Speed (m/min)	Suspended Solids (mg/L)	Turbid Area (sq m)
4	4.2	14
8	19.1	24.5

Suspended solids within 50 m of the dredge were estimated from graphs provided by Kaneko, Watari, and Aritomi (1984). Suspended solids at 1 and 7 m from the water surface and 1 m above the bottom were less than background.

Modified dustpan dredge

The US Army Corps of Engineers developed the dustpan dredge to remove free-flowing granular sediment from the Mississippi River. The dustpan dredge uses a dustpan-shaped dredgehead, with the aid of water jets to dislodge sediment from the channel bottom and to guide sediment into the suction inlet. Collected sediments are moved via centrifugal pumps.

Although the standard dustpan is not an innovative dredgehead, a modified dustpan dredgehead was tested in the James River, Virginia, (Figure 6) for removing contaminated fine-grained sediments. These tests were conducted by WES and the USAED, Norfolk, in 1982 (USAED, Norfolk 1982).

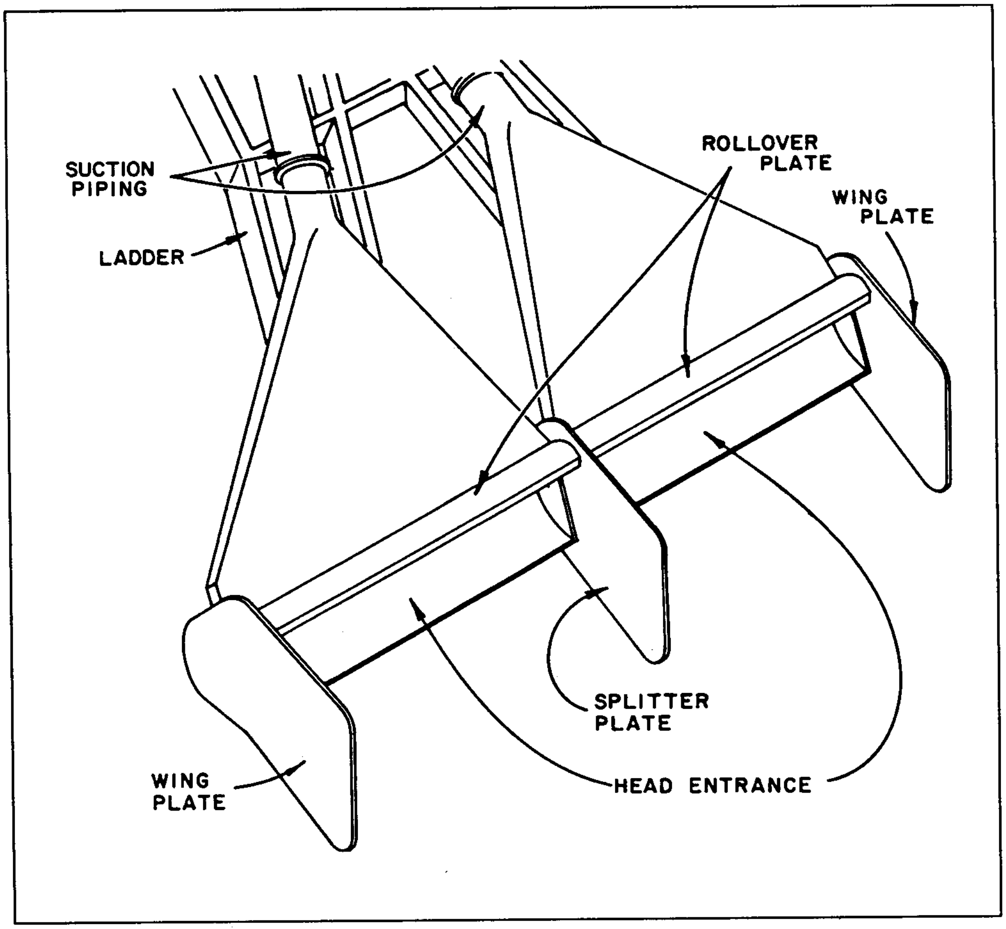

Figure 6. Modified dustpan dredgehead (from Hudson and Vann 1984)

Major design modifications included the following:

a. *Curved plate.* Mounted above the head opening much like a bulldozer blade, this plate improves the hydraulic condition of entry by creating a head of material over it and accelerating the material to entry velocity.

b. Winglets or splitters. Added to either end and center of the head to improve the containment of the sediment, stabilize the dustpan head, prevent spillage from the sides of the head, seal the head, and improve the suction conditions at the entry.

c. Trailing plate. Hinged below the head to act as a sealing strip, reducing material loss beneath the head and increasing suction efficiency.

The traditional cutterhead was replaced with a modified dustpan on the 18-in. hydraulic dredge *Essex*, owned by the Norfolk Dredging Company. The sediment at the dredge sites was a silty clay with a USCS classification of CH. Water depths in the area were approximately 7 m. Suspended solids concentrations around the dredgehead are reported in Table 6. The maximum average concentrations produced by the modified dustpan dredge over a tidal cycle, approximately 60 m downstream of the dredge, ranged from 100 mg/L near middepth to 300 mg/L near the bottom. Background concentrations at this site ranged from 53 mg/L near the surface to 90 mg/L near the bottom.

Table 6
James River Modified Dustpan Dredge Field Test (McLellan et al. 1989)

Day	Number of Samples	Suspended Solids at Dredgehead (mg/L)		
		Maximum	Minimum	Average
1	20	147	0	67
2	27	302	6	101
3	20	130	0	42
4	28	122	0	35

The modified dustpan dredgehead experienced repeated clogging and still produced a small sediment plume (Hudson and Vann 1984, Hayes 1986, McLellan et al. 1989). Sediment resuspension data associated with a cutterhead dredge operated during this test can be found in these references.

Disc-Bottom Dredges

Delft University in The Netherlands designed the disc-bottom dredgehead in the 1970s. It consists of a flat-bottom plate and top ring, with vertically placed cutting blades, rotating around a vertical axis with a suction mouth located inside the cutter (Van Raalte and Zwartbol 1986).

Specific data or information on the sediment resuspension characteristics of the disc-bottom dredgehead was not found in current literature.

Bucket Wheel Dredges

Researchers in the United States and The Netherlands designed the bucket wheel dredgehead. It is a combination of the positive aspects of the bucket-line and conventional cutterhead dredges. The bucket wheel consists of numerous overlapping bottom and backless buckets with a suction intake in the inner circumference of the wheel (Barnard 1978, Mitre Corporation 1983, Sorensen 1984).

The Japanese have developed a soft-sludge dredgehead that consists of a bucket-wheel cutter rotating perpendicular to the ladder with a pneumatic suction system, a shielded bucket wheel, and an underwater camera (Hamasuna 1990). The operation principle of these dredgeheads suggests that they may be effective at minimizing sediment resuspension. Specific data or information on sediment resuspension characteristics of the bucket-wheel dredgehead was not found in the current literature.

Cutter-Suction Dredges

Another conventional cutterhead innovation is the cutter-suction combination (Huston and Huston 1976, Barnard 1978). The cutter-suction combination uses the suction pipe as both the suction and the drive shaft of the cutter. This combination reduces the cutter size which, in turn, decreases the required torque to generate the necessary force on the cutter blades. The suction intake is located in the center of the cutter, allowing the suction to draw material more evenly from all directions, and enables the mouth of the suction to be a more hydraulically efficient bell shape. This location extends the suction farther into the cutter, decreasing the distance between the channel bottom and the intake. It is anticipated that these features may aid in the reduction of sediment resuspension. Although this design seems promising, it has received little attention.

Portable Hydraulic Dredges

In this context, portable dredges are those normally transported overland. Besides being convenient for isolated, hard-to-reach areas and economical for small dredging jobs, these small cutterhead dredges have been advertised as operating with limited sediment resuspension. However, limited data are available to verify these claims.

The Delta and horizontal auger dredges, developed in the United States, are two such portable dredges. The Delta dredge consists of a submerged pump located above two counter-rotating, reversible cutters and mounted on a pontoon hull. The horizontal auger dredge uses a shielded auger cutterhead to cut material and move it laterally toward the center of the auger, or the suction intake (Barnard 1978, Mitre Corporation 1983).

Tests in New Bedford Harbor compared the horizontal auger dredge with cutterhead and Matchbox dredges (Otis, Andon, and Bellmer 1990). Suspended solids concentrations at approximately 60, 120, and 150 m downstream of the dredge, at ebb tide, are reported in Table 7.

Table 7
New Bedford Horizontal Auger Dredge Field Test (Otis, Andon, and Bellmer 1990)

Day	Average Daily Suspended Solids at Middepth (mg/L)			
	At Dredgehead	60 m Downstream of Dredging Area	120 m Downstream of Dredging Area	150 m Downstream of Dredging Area
1	2,226	12	9	8
2	985	10	10	3
3	2,160	20	10	10
4	1,259	—	—	—

Note: Distances are approximate.

The horizontal auger dredge experienced problems with positioning, anchoring, and effectiveness of the mudshield. Sediment resuspension at the dredgehead was substantially higher than for either the cutterhead or Matchbox dredge.

Hopper Dredges

The hopper dredge is a self-contained seagoing ship used mainly for maintenance dredging in bar areas and shipping channels (Figure 7). Hopper dredges are commonly classified according to their hopper capacity. Large-class hopper dredges have hopper capacities of 6,000 cu yd or greater; medium-class hopper dredges have hopper capacities ranging from 2,000 to 6,000 cu yd; and small-class hopper dredges have hopper capacities of 500 to 2,000 cu yd (US Army Corps of Engineers 1983).

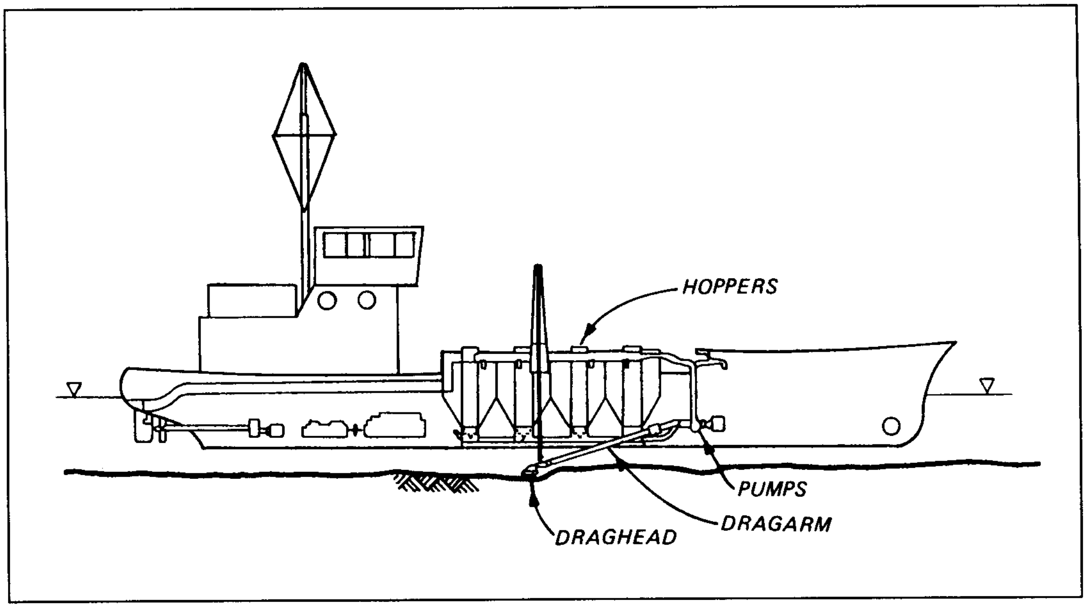

Figure 7. Hopper dredge (from McLellan et al. 1989)

The hopper dredge uses a draghead to remove sediment from the bottom of the channel. The sediment is loosened by the erosive and/or mechanical forces of the draghead, taken into the suction intake, and pumped into hoppers located onboard the dredge. Once filled, the dredge transports its load to the disposal site.

One or two dragarms can be mounted to the side or center line of the ship. Suspended solids around a nonoverflowing hopper dredge can range from 12 to 54 mg/L in the area of influence. Most of the sediment resuspension occurs in the lower water column near the cutting action (McLellan et al. 1989).

Overflowing dredge hoppers is common practice in many areas of the United States. Palermo and Randall (1990) explain the practices and problems associated with overflowing dredge hoppers. Overflowing dredge hoppers introduces an additional source of sediment to the water column; therefore, hopper overflow should not be allowed when dredging contaminated sediment. McLellan et al. (1989) and Hayes (1986) reported results of sediment resuspension associated with overflowing and nonoverflowing hopper dredges.

Historically, most dragheads dredge sand particles using erosive processes. Recently, dragheads have been designed to dredge fine-grained sediments using both erosive and mechanical action. An effectively designed silt draghead will dredge fine-grained sediment at higher densities than conventional dragheads, thereby reducing the amount of water in the hoppers. The front-open and IHC Roller Silt dragheads are two types of erosive/mechanical dragheads (Van Dooremalen et al. 1983).

Front-open draghead

The Japanese Port Construction Bureau developed the front-open draghead (Figure 8) (Irie 1984). Major features of the draghead include the following:

a. Mixing blades. Provide a uniform mixture to the suction system.

b. Stabilizers. Extend the capability of the swell compensators to follow the sea bottom in soft mud.

c. Angle control. Allows the bent part of the draghead to move.

d. Grates. Prevent large objects from clogging the suction intake.

e. Density detectors. Four sets measure the density of the dredged material and detect the mud layer.

f. Water jets. Aid in the removal of dense sediment; however, these should not be used when removing contaminated sediment.

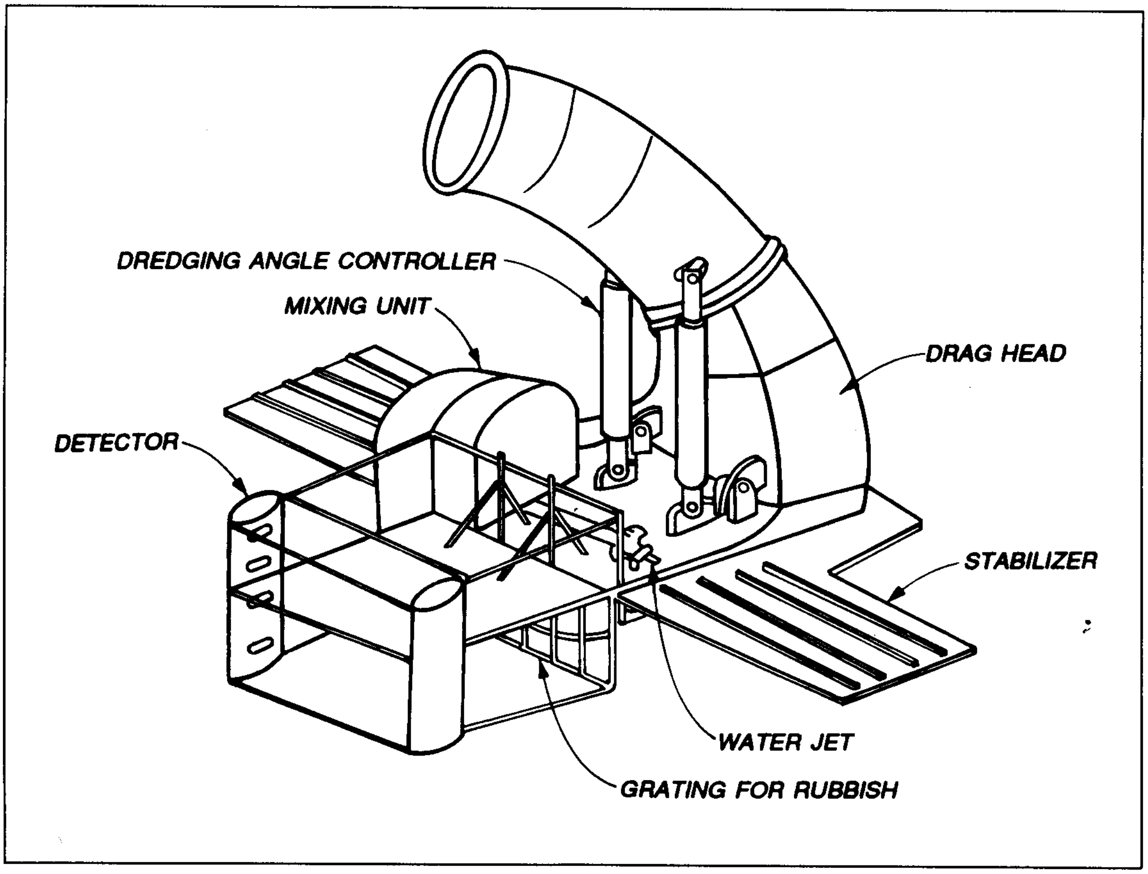

Figure 8. Front-open draghead (from Irie 1984)

Sediment resuspension associated with the front-open draghead has been monitored at Chiba, Nagoya, Mikawa, and Kinuura Ports in Japan. Descriptions of these field tests and the performance of the front-open draghead follow.

Chiba Port. In 1979, the trailing hopper dredge *Tokushun Maru* No. 1, with a hopper capacity of 4,091 cu m, tested the front-open draghead in Chiba Port. The draghead was designed specifically for the *Tokushun Maru* No. 1, based on the vessel's operating velocity and the capacity of the suction system. This draghead was an early version of the front-open draghead and did not include angle control or water jets. The sediment at the site was a clayey silt, and the average water depth was 13 m. Suspended solids concentrations at the middle of the dragarm were 15 mg/L or less, and most of the concentrations at the draghead were 10 mg/L or less. Draghead concentrations greater than 30 mg/L, measured during each of the 47 test runs, are provided in Table 8 (Irie 1984). These high concentrations normally occurred while raising the draghead off the bottom or moving the draghead through the sediment at a high velocity.

Table 8
Chiba Port Front-Open Draghead Field Test (Irie 1984)

Test Number	Suspended Solids at Draghead Greater Than 30 mg/L (in mg/L)
T 5–4	130
T 6–2	600
T 6–3	2,500
T 6–4	8,400
	4,600
T 9–2	6,300
	320
T 9–4	300
T 12–4	40–60
	3,400
T 13–2	1,300

Nagoya Port. In 1980, the trailing hopper suction dredge *Seiryu Maru*, with a hopper capacity of 1,754 cu m, tested the front-open draghead in Nagoya Port. The draghead used in this test was similar to the one used in Chiba Port.

The sediment at the site was a clayey silt, and the depth of the seabed was uneven with depths ranging from 8 to 10 m. The uneven seabed made positioning of the draghead difficult. Suspended solids were measured at the draghead and on the dragarm during 32 test runs. Suspended solids readings during this test were reportedly high. A graph of suspended solids versus depth of dredging indicated that numerous readings between 500 and 2,000 mg/L were measured (Irie 1984).

Mikawa Port. In 1981, the *Seiryu Maru* tested a modified front-open draghead in Mikawa Port, Japan. Modifications to the draghead included a larger stabilizer, dredging angle controller, and water jets. The sediment at this site was a clayey silt with water depths ranging from 12 to 14 m.

Suspended solids were measured at the draghead and on the dragarm during 28 test runs. Although background suspended solids readings were not reported, suspended solids concentrations around the draghead were reported to be 10 times background during stable dredging. Concentrations of 5,000 mg/L were measured when the buried draghead was lifted out of the sediment (Irie 1984).

Kinuura Port. A field test was conducted in 1981 in Kinuura Port using a front-open draghead mounted on the *Seiryu Maru* hopper dredge. Sediment resuspension associated with the front-open draghead, with and without stabilizers, was measured. In addition, tests were conducted on the effectiveness of the draghead's stabilizers and mud detectors. The dredged material was a silty clay; however, no water depths were provided (Okayama 1983).

Sediment resuspension was measured with submerged pumps located on the dragarm, draghead, and at "proper" locations downstream of the dredge. Sediment resuspension was estimated from a graph provided by Okayama (1983). Suspended solids concentrations at the draghead, without stabilizers, ranged from 10 to 13,000 mg/L. Suspended solids at the draghead, with stabilizers, ranged from 10 to 11,000 mg/L. High-end concentrations were reportedly associated with quick removal of the draghead from the sea bottom.

Concentrations reportedly leveled off at or below 1,000 mg/L during stable dredging with and without stabilizers. Maximum SS concentrations measured at the dragarm and the proper location downstream during stable dredging were 11.8 and 5.8 mg/L, respectively. Therefore, sediment resuspension associated with the front-open draghead, with and without stabilizers, appears to be limited to the immediate vicinity of the draghead.

IHC roller silt dragheads

Description. MTI Holland laboratory of IHC Holland, The Netherlands, developed the IHC Roller Silt draghead (Figure 9) (Van Dooremalen et al. 1983). Major features of the draghead include the following:

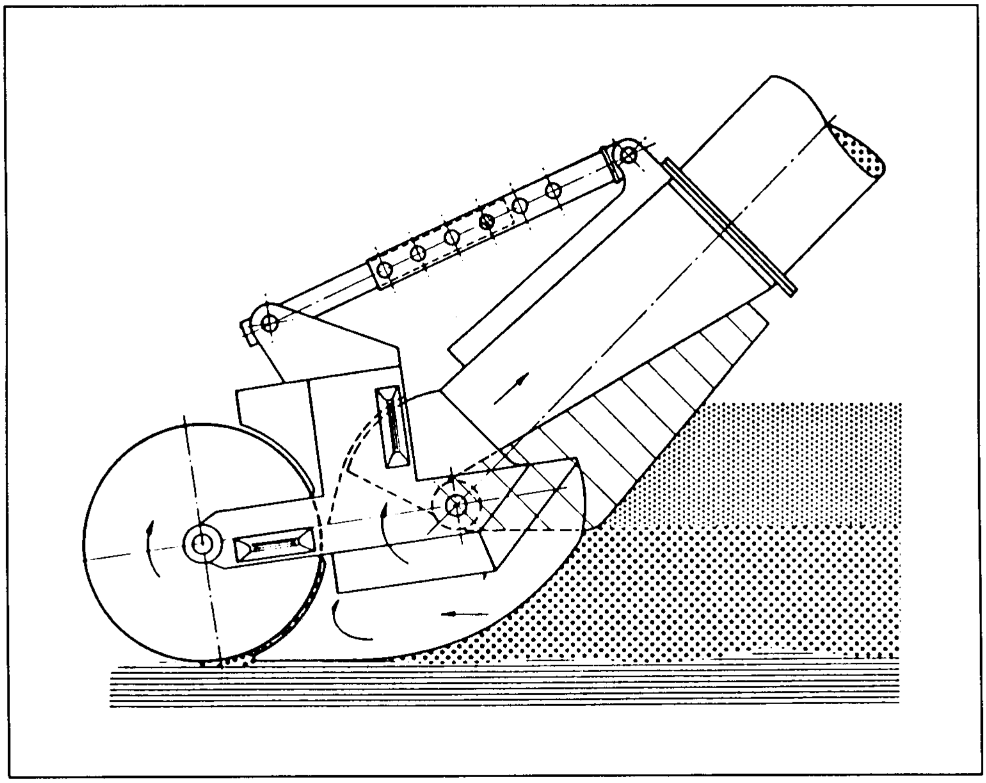

Figure 9. IHC Roller Silt draghead (from Van Dooremalen et al. 1983)

a. Roller. Breaks the cohesion of the sediment, supports the draghead, prevents accumulation of silt behind the draghead, passes over obstructions, and lessens the friction between the bottom and draghead.

b. Adjustable suction inlet. Adjusts to the thickness of sediment being removed, suction depth, and trailing speed.

Sediment resuspension associated with the IHC Roller Silt draghead has been monitored at Gray and Pearl Harbors in the United States. Descriptions of these field tests and the performance of the IHC Roller Silt draghead follow.

Gray and Pearl Harbors. In 1983 and 1984, the USAED, Portland, conducted field studies in Gray Harbor, Washington, and Pearl Harbor, Hawaii, to compare the effectiveness of several hopper dredge dragheads designed for dredging fine-grained sediments. The hopper dredge *Essayons*, with a hopper capacity of 6,000 cu yd, was used for these tests.

Dragheads tested included those of IHC California; Biddle California, modified with skirts and a mixing valve; Portland Mud; Comber Class Coral, without teeth or skirt but with a mixing valve; and IHC Roller Silt dragheads with grates added to prevent clogging. The IHC California draghead was installed on the starboard dragarm, as the control item, while the other dragheads were installed on the port dragarm for comparison.

The dredged material was a sandy silt with a USCS classification of ML. Sediment resuspension of the entire dredge was observed as opposed to the resuspension from a particular draghead (Case, Woolley, and Perkins 1984; McLellan et al. 1989).

The results of this testing indicated that the IHC Roller Silt and Portland Mud dragheads were the most effective in dredging fine-grained sediments in Gray and Pearl Harbors. The IHC Roller Silt draghead experienced problems with clogging; however, it seems to have the potential to operate well in fine-grained sediments if the clogging problem can be resolved.

It appears that the physical components of the hopper dredge (pump size and location, draghead design, pipe size, etc.) are the major factors affecting its efficiency in dredging fine-grained sediments. If the physical components of the hopper dredge can be improved so they would not be the limiting factors of production, the draghead design could be improved.

3 Pneumatic Dredging Equipment

General

Pneumatic pumps use a positive displacement action capable of pumping slurry at higher solid concentrations than centrifugal pumps. Pneumatic pumps are also capable of delivering significantly higher heads than centrifugal pumps (Courtney 1986). They are, however, more expensive in terms of capital and operating costs than centrifugal pumps. Thus, pneumatic dredges have received limited use in the highly competitive US dredging market.

While some debate exists over the cost of the pneumatic dredge, the generally passive nature of this dredge makes it a logical candidate for removing highly contaminated sediments. Some pneumatic dredges employ mechanical action to loosen sediments for removal, but they are generally less aggressive than conventional dredges. Operational characteristics and considerations are discussed in the dredge descriptions which follow.

Pneuma, Oozer, and airlift dredges are equipped with pneumatic pumping systems. Although there are some structural differences between the Pneuma and Oozer dredges, the basic operating principle is the same. The natural positive water pressure is combined with an artificially generated negative pressure, usually inside a submerged cylinder, to create large vacuum pressures on the sediment. Deep dredging depths provide a stronger thrust because of increased hydrostatic pressure; however, vacuum systems can be added to the system to make up for losses in hydrostatic pressure in shallow environments.

Once the sediment moves into the vacuum of the submerged cylinder, it is discharged by pumping compressed air into the cylinder and providing a low-pressure exit via a pipe reaching above the water surface.

The complete dredging process therefore includes the suction, discharge, and pressure-releasing steps illustrated in Figure 10 and described below (Nishi 1976, Barnard 1978).

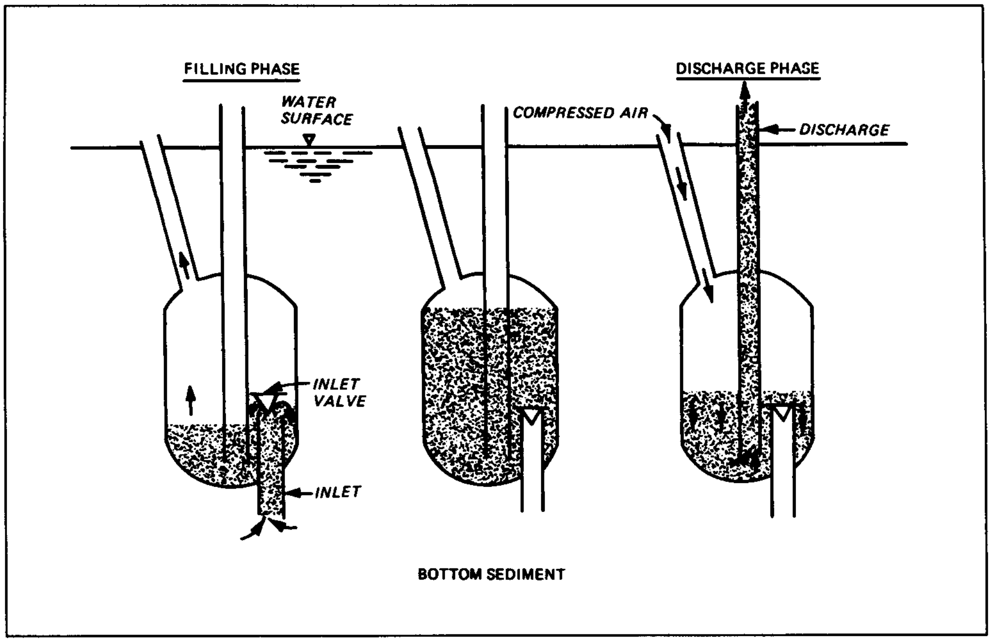

Figure 10. Pneumatic pump operation (from Herbich and Brahme 1991)

a. As a vacuum occurs inside the tank, sediment moves through the inlet valve, as a result of the difference in pressure inside and out (i.e., water pressure plus vacuum), and flows into the submerged cylinder. Once the cylinder is filled, the suction cycle automatically ends.

b. The cylinder is opened to the atmosphere, and the air compressor delivers compressed air to the cylinder. The positive pressure created in the cylinder causes sediment to move through the outlet valve until the cylinder is emptied.

c. Upon completion of the suction and discharge processes, residual pressure inside the cylinder is released into the air and the operation repeats. Sediment flows into the submerged cylinders continuously as the suction and discharge processes alternate.

Pneuma Dredges

Description

SIRSI of Florence, Italy, initially developed the Pneuma dredge (Figure 11). Several standard models (30/5 to 1500/200) of the Pneuma pump are currently available from Pneuma S.R.L. of Firenze, Italy. The

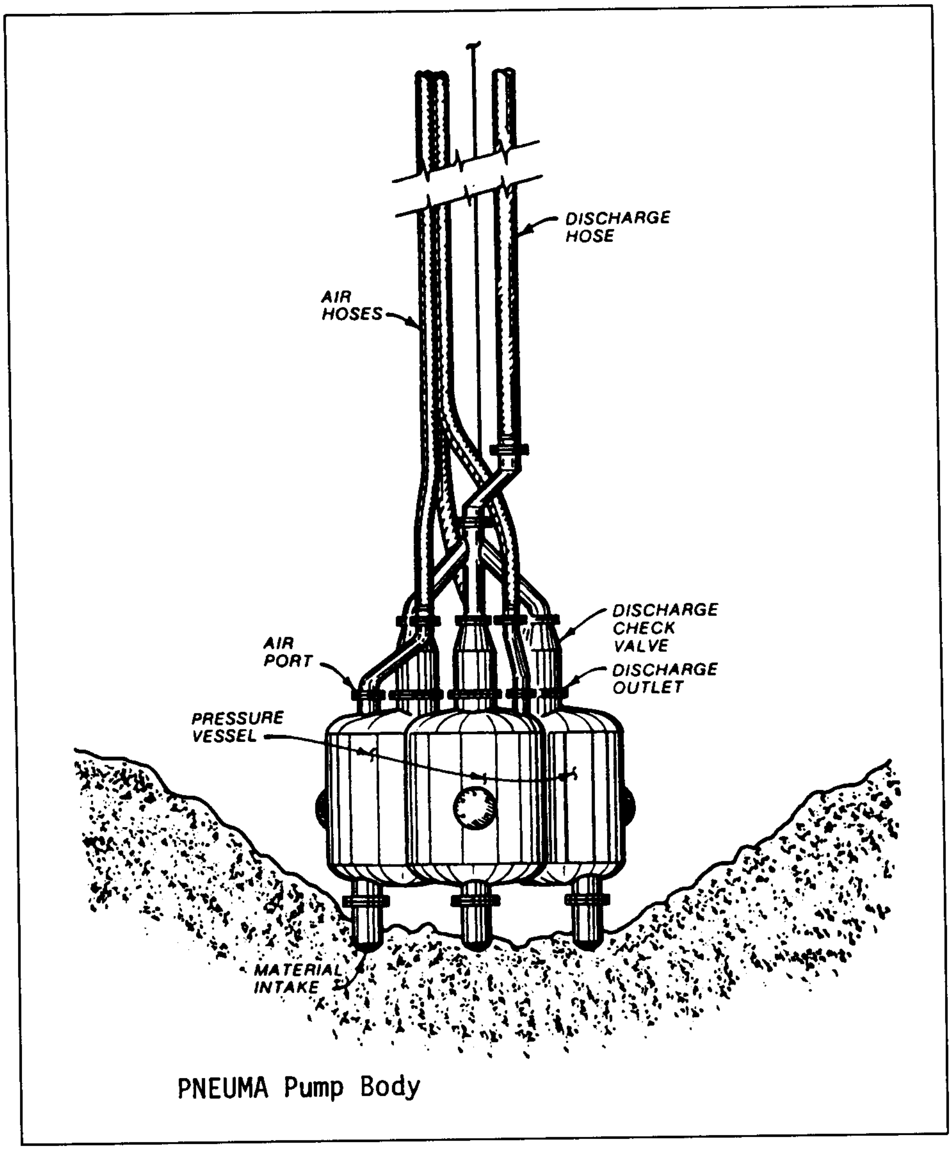

Figure 11. Pneuma dredgehead (from Herbich and Brahme 1991)

Pneuma dredge can operate by the hole, trailing, or ladder-mounted method.

The hole method consists of a crane-mounted pump dredging a hole, with the surrounding material flowing into the hole. This method is most effective in loose, cohesionless material.

The trailing method consists of winching a barge or ladder-mounted pump through the sediment. This method is normally used for cohesive material.

Ladder-mounted versions of the Pneuma dredge operate much like the conventional cutterhead dredge and are applicable to similar dredging conditions.

With the cutting action of a Pneuma dredgehead in the lower water column, most of the sediment resuspension should appear in the lower water column (Barnard 1978; Kasajima 1984; Richardson et al. 1984; Pneuma S.R.L., undated; Faldi 1990).

Major features and functions of the Pneuma dredge are listed below.

a. Three submerged cylinders. Collect the sediment.

b. Distributor. Regulates the influx and discharge of compressed air to and from each cylinder of the pump body. The distributor is normally located on the dredge deck; however, it can be mounted on top of the cylinders when dredging in deep water.

c. Air compressor(s). Provides a high-pressure air source.

d. Hole dredging attachment. Three straight-leg attachments are fitted to the bottom of the cylinders and used to remove free-flowing sediment.

e. Trail dredging attachment. One big shovel is normally used for removing semihard material; either one or three small shovels would be used for removing hard material; three small vacuum shovels would be used to remove thin layers of sediment or sediment from concrete or stone surfaces. Two small shovels or two big shovels are mounted on the starboard and port sides of the pump when it is ladder-mounted. All of these attachments are fitted to the bottom of the cylinders and are designed to penetrate stiff sediment and level the bottom. Grates can be used to prevent large objects from entering the attachments and clogging the suction intake.

f. Vacuum system. Aids in the removal of sediment in shallow water depths.

g. Check valves. Allow flow in only one direction.

Sediment resuspension associated with the Pneuma dredge has been monitored in the Duwamish Waterway, Cape Fear River, and Gibraltar Lake in the United States and in the Aji River and Chofu and Kokura Ports, Japan. Descriptions of these field tests and the performance of the Pneuma dredge are given in the following paragraphs.

Field tests

Duwamish Waterway. In March 1976, the USAED, Seattle, used a Pneuma dredgehead to remove sediments contaminated with polychlorinated biphenyls (PCBs) from Slip 1 of the Duwamish Waterway located in Seattle Harbor, Washington. An Italian-manufactured Pneuma model 600/100 dredge, obtained from Pneuma North America, Inc., Hinsdale, IL, performed the dredging. A debris boat (the *Puget)* used a crane to deploy the Pneuma dredgehead in the first USACE use of a Pneuma dredge. Downstream monitoring reportedly indicated that the Pneuma pump produced little resuspension (USAED, Seattle 1976; Herbich and Brahme 1991).

Cape Fear River. The WES and the USAED, Wilmington, conducted tests on the 600/100 model Pneuma dredgehead between August and October 1978. At that time, SIRSI-SpA of Florence, Italy, manufactured the Pneuma pump, which was obtained from Amtec Development Corporation, Highland Park, IL. The dredging was conducted in a lock approach, tidal inlet, and dock area in the Cape Fear River, North Carolina. The Pneuma dredged sand from the lock approach and tidal inlet, and silty clay from the dock area.

Sediment resuspension was monitored during dredging of the silty clay around wharf No. 3 at the Military Ocean Terminal at Sunny Point, which is located along the Cape Fear River. Water depths at the Terminal site ranged from 8 to 9 m.

A 32-m-long boat (the *Snell*), equipped with a 18-ton crane, deployed the Pneuma dredgehead. The dredgehead was towed through the sediment by the *Snell* (Richardson et al. 1982, Richardson 1984, Raymond 1984).

Measurements of average suspended solids are provided in Table 9. Background concentrations taken at the water surface adjacent to the dredgehead while the dredge was not operating averaged 5.44 mg/L.

Results indicated that turbidity generation was limited and intermittent, with no apparent suspended material buildup. The crane-based and towing deployment method was not conducive for good pump performance and sustained excavation rates. Because of its weight and bulk, the model tested was difficult to deploy properly without more appropriate equipment.

Gibraltar Lake. From August 1984 to May 1986, the city of Santa Barbara, CA, undertook a dredging project in Gibraltar Lake. Gibraltar Lake is located about 7 miles north of Santa Barbara and provides an average of 35 percent of the city's drinking water supply. The lake's capacity has been steadily decreasing because of siltation from the stripped land adjacent to the lake, as a result of numerous forest fires in the area. In addition, a portion of the sediment in the lake was contaminated by discharges into the lake from an old mercury-mining mill.

Table 9
Cape Fear River Pneuma Dredge Field Test (Richardson et al. 1982)

Location (Downstream of Dredgehead, ft)	Average Suspended Solids (mg/L)			
	Water Surface	5-ft Depth	10-ft Depth	15-ft Depth
0	4.63	5.60	5.52	10.93
25	5.35	6.42	12.00	15.28
50	7.02	5.65	7.40	8.50
75	5.23	7.90	6.18	14.38
100	5.30	5.15	5.45	6.70
125	4.65	5.15	4.95	4.90
150	6.35	9.35	12.25	14.55
175	4.80	2.05	7.00	18.50
200	4.85	4.30	8.70	11.70

A Pneuma dredge was selected to remove the silty sediment from the lake because of concern over the city's water supply. Water depths in the lake ranged from 15 to 25 ft. The Pneuma dredge was purchased by the USEPA Clean Lakes Program and the city of Santa Barbara. Originally, the dredge was equipped with straight-leg attachments for removal of the loose sediment. Later, the straight-leg attachments were replaced with the three-shovel attachments for removal of the more consolidated sediment. The Pneuma dredge reportedly performed very well. Upon completion of the initial phases of dredging, the city has maintained the dredge for future use in the lake (City of Santa Barbara 1987).

Weekly water quality analyses were performed by the city of Santa Barbara. These analyses included monitoring of suspended solids at the water surface and at middepth, at the dredge and 61 m from the dredge. Results of this monitoring are reported in Table 10.

Aji River. In March 1979, the Port and Harbour Bureau, city of Osaka, Japan, conducted turbidity field tests in the Aji River using a 450/80 Pneuma dredge and a watertight bucket (see Chapter 4). A Pneuma dredgehead, with three shovel attachments, was mounted on the ladder of the dredge *ShunKai*. Previous tests indicated that the three-shovel attachment was more effective than the big shovel and straight-leg attachments when dredging mud and soft clays. In shallow depths, the surplus of compressed air was used to drive a vacuum that decreased the minimum dredging depth by 1 m and reduced the chances of choking the shovels with soft clay.

Table 10
Gibraltar Lake Pneuma Dredge Field Test
(City of Santa Barbara 1987)

Day	Suspended Solids at Dredgehead (mg/L)		Suspended Solids 61 m from Dredge (mg/L)	
	Surface	Middepth	Surface	Middepth
1	7.2	9.3	9.2	7.8
2	1.8	1.7	3.3	3.2
3	2.3	2.6	1.2	1.5
4	0.6	1.2	3.3	1.5
5	1.5	0.8	1.3	1.4
6	1.0	1.1	0.8	1.2
7	21.6	23.2	22.8	—
8	3.5	3.0	2.0	3.0
9	8.0	8.0	8.0	12.0
10	5.9	5.8	5.4	5.2
11	3.6	3.6	2.7	3.8
12	0.9	1.2	1.2	1.0
13	0.5	0.7	0.3	0.3

The dredged material at this site consisted of soft clay in water depths ranging from 9 to 12 m (Kasajima 1984). Suspended solids concentrations were measured at 50, 100, and 150 m upstream and downstream and at 50 and 100 m starboard and port of the Pneuma dredge. These measurements are presented in Table 11.

Chofu Port. In August 1973 the Japanese conducted field tests using a ladder-mounted 300/60 model Pneuma dredge in Chofu Port. Chofu Port is located near Shimonoseki City. The Pneuma dredge *No. 3 Suehiro* was used for this project in water depths that ranged from 4 to 5 m. Turbidity was measured at the water surface and at 4, 2, and 1 m from the sea bottom at 11 sampling locations. However, Pneuma S.R.L (undated) reported the suspended solids at this site to be equivalent to 2.696 times the turbidity readings. Using this conversion, the results are provided in Table 12 (Pneuma S.R.L., undated; Barnard 1978).

Kokura Port. In December 1973 the Japanese conducted field tests using a ladder-mounted 300/60 model Pneuma dredge in Kokura Port. Kokura Port is located near Kita Kyushu City. The Pneuma dredge *No. 3 Suehiro* was used for this project in water depths that ranged from 9.5 to 10 m.

Table 11
Aji River Pneuma Dredge Field Test (Kasajima 1984)

Location (From Dredge)	Suspended Solids (mg/L)		
	0.5 m Below Water Surface	2 m Below Water Surface	2 m Above Water Bottom
50 m bow	13	11	8
100 m bow	13	11	4
150 m bow	13	10	4
50 m port	12	10	6
100 m port	12	11	5
50 m stern	14	10	10
100 m stern	14	9	9
150 m stern	14	9	7
50 m starboard	12	10	6
100 m starboard	13	11	6

Table 12
Chofu Port Pneuma Dredge Field Test (Pneuma S.R.L., undated)

Sample Location	Suspended Solids[1] (mg/L)			
	Water Surface	4 m from Bottom	2 m from Bottom	1 m from Bottom
30 m in front of dredgehead	12.4	17.5	18.3	12.4
50 m port of dredgehead	6.5	6.5	7.3	7.8
50 m starboard of dredgehead	5.7	5.7	7.8	15.9
30 m behind dredge	4.6	1.3	10.0	10.0
5 m port of dredgehead	30.2	4.9	8.6	11.1
5 m starboard of dredgehead	1.3	2.2	2.2	2.2
5 m in front of dredgehead[2]	4.1	9.8	25.7	48.0
5 m behind dredgehed	9.2	6.2	12.9	8.1
Port bow of dredge	12.1	2.2	3.2	7.3
Starboard bow of dredge	7.8	12.9	16.7	12.9
Midstern of dredge	11.3	13.5	44.5	28.5

[1] Calculated using SS = 2.696 × turbidity.
[2] Measured directly, no conversions.

Turbidity was measured at the water surface and at 4, 2, and 1 m from the sea bottom at eight sampling locations. However, Pneuma S.R.L (undated) reported the suspended solids at this site to be equivalent to 1.2326 times the turbidity readings. Using this conversion, the results are provided in Table 13 (Pneuma S.R.L., undated; Barnard 1978).

Table 13
Kokura Port Pneuma Dredge Field Test (Pneuma S.R.L., undated)

Sample Location	Suspended Solids (mg/L)[1]			
	Water Surface	4 m from Bottom	2 m from Bottom	1 m from Bottom
50 m in front of dredgehead	11.1	11.7	10.5	11.7
50 m port of dredgehead	9.9	9.9	11.1	12.3
50 m behind dredgehead	6.2	3.7	2.5	4.3
50 m starboard of dredgehead	9.2	6.8	22.2	—
5 m port of dredgehead	6.2	4.9	8.6	9.9
5 m starboard of dredgehead	7.4	8.0	8.0	12.9
100 m port of dredgehead	4.9	6.8	8.0	7.4
100 m behind dredgehead	5.5	6.8	6.8	8.0

[1] Calculated using SS = l.2326 × turbidity.

Oozer Dredges

Description

Toyo Construction Company, Ltd.,[3] developed the Oozer dredge (Figure 12) for removing highly contaminated sediments, but the Japanese Ministry of Construction owns the basic patent on the Oozer dredge. It is reportedly available in the United States through TJK, Inc., of California (Goodier 1981).

The Oozer dredge is a Japanese version of the Pneuma dredge. The Oozer dredge is ladder-mounted and operates much like a conventional cutterhead dredge. With the cutting action of Oozer dredgehead in the

[3] 3–7–1 Kanda Nishikicho, Chiyoda-ku, Tokyo, Japan.

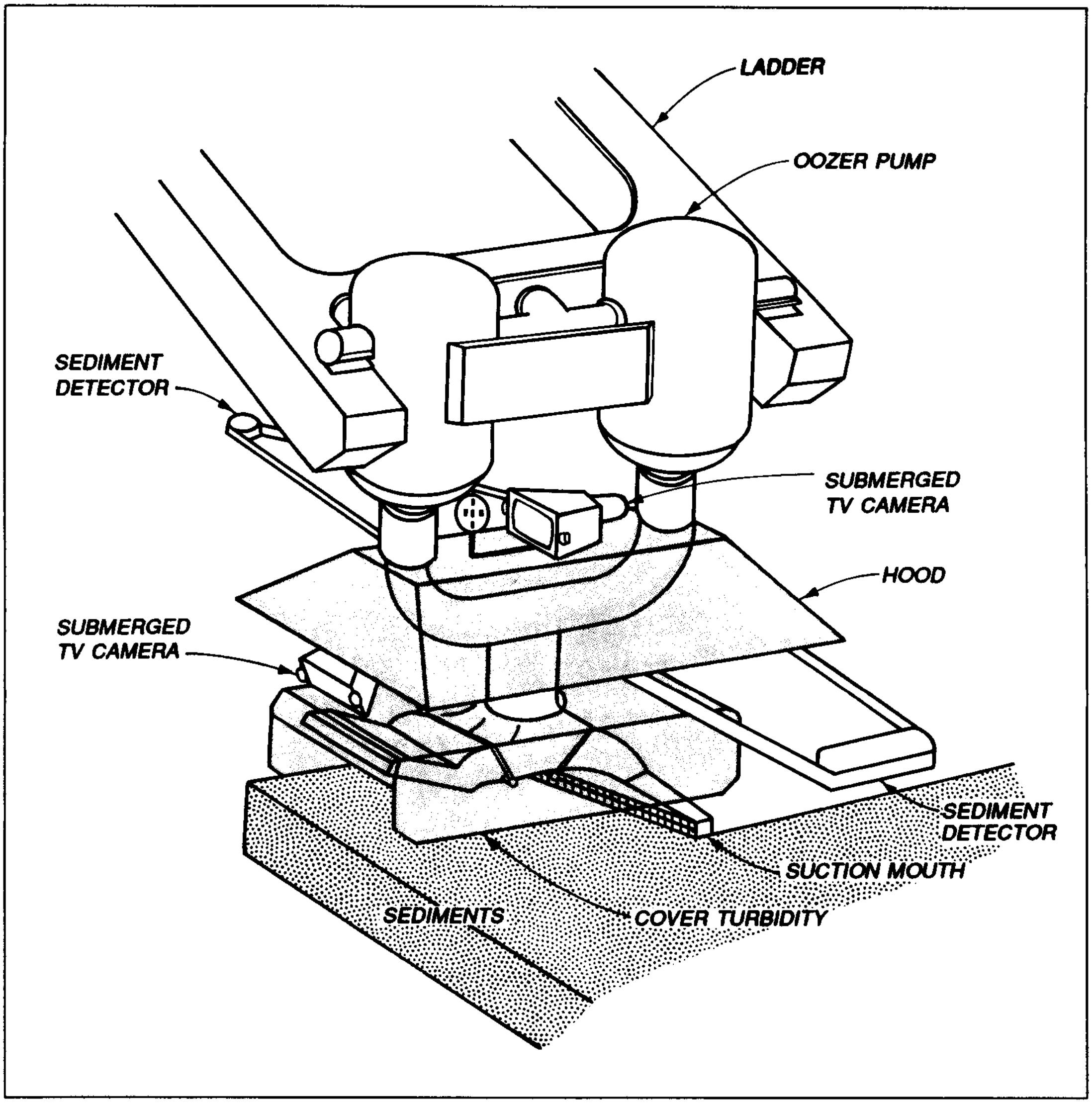

Figure 12. Oozer dredgehead (from Toyo Construction Company, undated)

lower water column, most of the sediment resuspension should appear in the lower water column (Nishi 1976; Barnard 1978; Toyo Construction undated, 1978; Mitre Corporation 1983; Fujii and Otsu 1987).

Major features and functions of the Oozer dredge include the following:

a. Two submerged cylinders. Collect the sediment.

b. Distributor. Regulates the influx and discharge of compressed air to and from each cylinder of the pump body. The distributor can be mounted on top of the cylinders when dredging in deep water.

c. Air compressor(s). Provides a high-pressure air source.

d. Vacuum system. Aids in the removal of sediment in shallow depths because of a deficiency of hydrostatic pressure.

e. Cutters. Draghead or hydraulic screw cutters with grates to prevent large objects from clogging the suction intake.

f. Covers. Located over the suction mouth to recover released oil and gas and directly below the two cylinders to prevent sediment resuspension.

g. Sonar. Positioned on the upper side of the suction mouth to allow the dredgehead to follow the contours of the bottom.

A volume recorder and underwater camera may also be attached to the Oozer dredgehead. The volume recorder records the actual amount of material dredged, and the underwater camera monitors the amount of sediment resuspension. Toyo Construction Company currently operates two Oozer dredges, the *Taian Maru* and the *No. 1 Oozer.*

Field tests

Osaka Bay. The Japanese Dredging and Reclamation Engineering Association conducted a field test of the Oozer dredge in Osaka Bay, Japan. The Oozer dredge removed organically contaminated fine-grained sediment in 16 m of water. Results indicated that the primary source of sediment resuspension around the Oozer dredge is the swing speed.

Suspended solids concentrations were monitored at locations 50, 100, 200, and 300 m in front of the Oozer dredgehead; three sample stations were radially located at these distances. The maximum concentrations observed at the three stations, as approximated from graphs provided by Koba and Shiba (1981), are provided in Table 14. Koba and Shiba (1981) reported background suspended solids ranging from 9 to 10 mg/L.

Table 14
Osaka Bay Oozer Dredge Field Test

Day	Depth (m)	Maximum Suspended Solids[1] (mg/L)			
		50 m in Front of Dredgehead	100 m in Front of Dredgehead	200 m in Front of Dredgehead	300 m in Front of Dredgehead
1	3	12	10	11	5
	8	10	9	10	8
	12	9	7	7	8
2	3	11	12	10	6
	8	11	14	9	2
	12	11	13	13	5

[1] Approximated from graphs provided by Koba and Shiba (1983).

Airlift Dredges

The airlift dredge consists of a submerged recovery pipe into which compressed air is injected at a point below the water surface. As the air and water flow into the submerged end of the recovery pipe, the sediment is picked up and transported through the pipe to the surface where the solid/water mixture is discharged into a recovery barge. The recovery pipe is positioned so that most of the disturbed sediment is drawn directly into the intake of the recovery pipe.

The operation principle of the airlift dredge reportedly minimizes sediment resuspension; however, no data were available to verify this. An airlift dredge and ancillary equipment capable of removing small amounts of sediment can be fabricated from readily available equipment (Goodier 1981, Mitre Corporation 1983).

4 Mechanical Dredging Equipment

Clamshell or bucket, ladder, and dipper dredges are generally classified as mechanical dredges because they accomplish sediment removal and movement through entirely mechanical means. Mechanical dredges are typically less efficient sediment movers than other dredge types, but are usually less expensive to mobilize, can operate in constricted areas, and produce dredged material concentrations nearer those of the in situ sediment. They are often selected for smaller dredging projects in constricted areas such as piers and docks. They also operate effectively in areas where waterborne traffic should not be interrupted or, because of distance, dredged sediment must be barged to the disposal site.

For these reasons, clamshell or bucket dredges are logical selections for removing sediments from many contaminated areas. Ladder and dipper dredges have characteristically high sediment resuspension rates and would not be suitable for dredging contaminated sediments (Mitre Corporation 1983).

Bucket Dredges

General

The bucket dredge is the most common mechanical dredge in the United States. Bucket dredges are often as simple as a crane mounted on a barge (Figure 13), but most are designed and constructed specifically for dredging. Size classification is by bucket capacity, ranging from 1 to 50 cu yd (Barnard 1978, Cullinane et al. 1986). A bucket dredge operates similarly to a land-based crane and bucket. The crane allows the bucket to fall through the water column, sinking into the sediment on contact; it then lifts the loaded bucket, causing the jaws to close, and raises the bucket through the water column. Once above the water surface, the crane rotates the bucket over the barge or open-water discharge area, and drops the bucket to release its load.

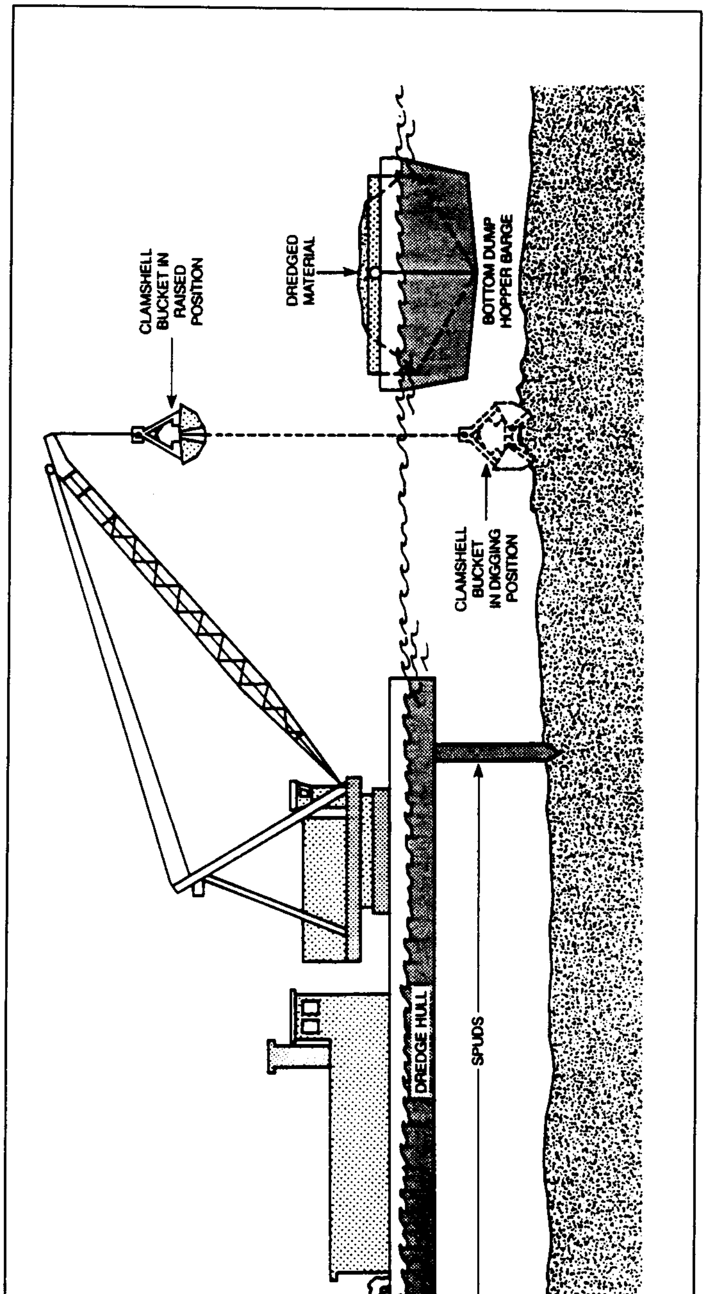

Figure 13. Mechanical dredge (from Palermo et al. 1989)

Sediment resuspension during bucket dredging operations results from the impact, penetration, and removal of the bucket from the bottom sediments; leakage while raising it through and out of the water column; and washing during movement through the water column (Barnard 1978). Substantial suspended solids may also occur if the sediments are loaded into a hopper barge and surface water in the barges is allowed to flow back into the water body. Suspended solids in the area of influence of the bucket dredge, without hopper barge overflow, can range from 20 to 1,100 mg/L (McLellan et al. 1989).

An enclosed, or watertight, bucket has been developed to limit spillage and leakage from the bucket, subsequently reducing sediment resuspension (McLellan et al. 1989). Recently, geotextile turbidity curtains, or turbidity screens, have been used to surround the point of dredging and contain the sediment resuspension (Hoogerwerf 1990, Pennekamp and Quaak 1990).

Watertight bucket

The Japanese Port and Harbor Institute developed the watertight bucket, which is manufactured by Mitsubishi Seiko Company, Ltd.[4] (see Figure 14). According to the manufacturer, bucket sizes range from 2 to 20 cu m. Several US manufacturers have produced watertight buckets with variations of the original design (Barnard 1978).

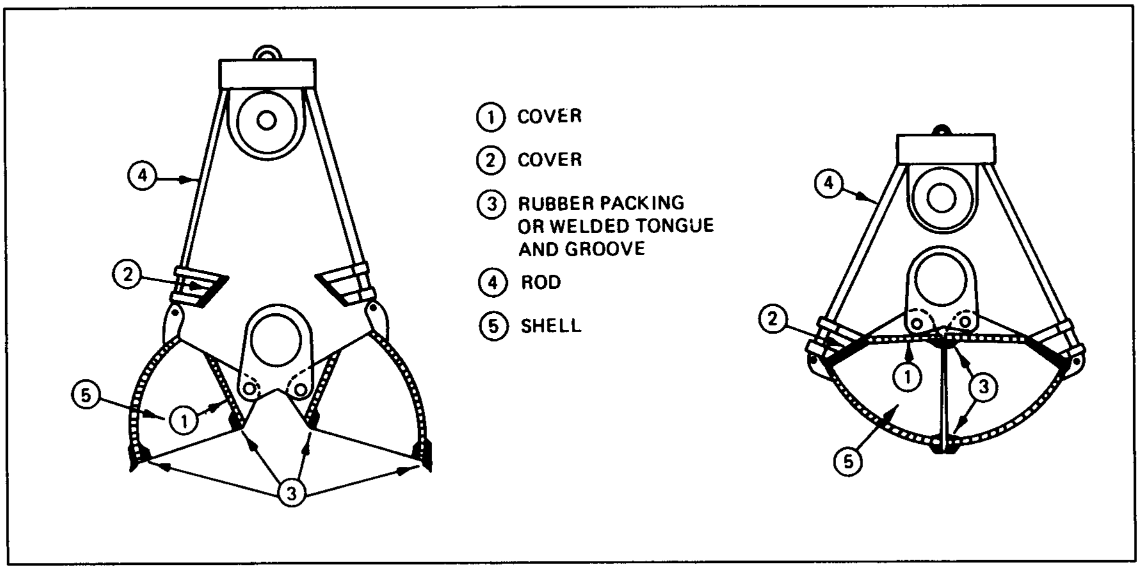

Figure 14. Watertight bucket (from Herbich and Brahme 1991)

[4] Box 48, Nippon Building, 2–6–2 Itemachi Chiyoda-ky, Tokyo, Japan.

Major features and functions of the original watertight bucket include the following:

a. Cover. Attached to the rods and shells of the bucket to prevent the material from spilling over the sides of the bucket while raising it through the water column.

b. Exterior pulley. Attached to the bucket covers, thereby eliminating the need for an opening in the bucket cover for the pulley cables.

c. Sealed joints. Rubber packing or tongue-in-groove joints seal the joints of the bucket.

Sediment resuspension associated with the watertight bucket has been measured in the Aji, Hori, and Oyabe Rivers in Japan and in the St. Johns River in the United States. Descriptions of these field tests are presented below.

Aji River. In March 1979, the Port and Harbour Bureau, city of Osaka, Japan, conducted turbidity field tests in the Aji River using a 450/80 Pneuma dredge and a watertight bucket. The size of the watertight bucket was not reported. The dredge material at this site consisted of soft clay in water depths ranging from 9 to 12 m (Kasajima 1984).

Suspended solids concentrations were measured at 50, 100, and 150 m upstream and downstream, 50 and 100 m port, and 50 m starboard of the watertight bucket dredge at 0.5 and 2 m from the water surface and 2 m from the water bottom. These measurements are provided in Table 15.

Hori River. In October 1973, a comparison between a 1-cu m conventional bucket and a 1-cu m Japanese watertight bucket was conducted in the Hori River near Nagoya, Japan. The removed sediments were primarily clay and silt in water depths of approximately 3 m. A hydraulic load meter connected to the wire rope of the bucket measured the average leakage weight from each bucket. This weight was determined after holding the bucket above the water surface for a period of 1 min for drainage to occur. Results indicated that the average leakage weight for the open bucket was 1.56 times that of the watertight bucket (Yagi, Koiwa, and Miyazaki 1976).

Suspended solids concentrations were monitored at locations 7, 13, and 23 m downstream of the watertight bucket at depths of 0.5, 1.5, and 2.5 m. The maximum concentrations observed, as approximated from graphs provided by Yagi Koiwa, and Miyazaki (1976), are provided in Table 16. Background suspended solids concentrations at this site ranged from approximately 5 to 12 mg/L. Sediment resuspension data associated with an open bucket operating at this site can be found in Yagi, Koiwa, and Miyazaki (1976).

Table 15
Aji River Watertight Bucket Field Test (Kasajima 1984)

Location (from Dredge)	Suspended Solids (mg/L)		
	0.5 m Below Water Surface	2 m Below Water Surface	2 m Below Water Bottom
50 m bow	20	38	40
100 m bow	13	12	9
150 m bow	13	12	12
50 m port	16	35	80
100 m port	15	14	7
50 m stern	15	14	30
100 m stern	14	18	25
150 m stern	14	13	25
50 m starboard	23	—	13

Table 16
Hori River Watertight Bucket Field Test

Depth (m)	Maximum Suspended Solids[1] (mg/L)		
	7 m Downstream of Bucket	13 m Downstream of Bucket	23 m Downstream of Bucket
0.5	105	—	—
1.5	70	25	—
2.5	20	13	30

[1] Approximated from graphs provided by Yagi, Koiwa, and Miyazaki (1976).

Oyabe River. In November 1973, the sediment resuspension associated with a 4-cu m watertight bucket was observed in the Oyabe River in Toyama Prefecture. Four separate tests were conducted at this site. The removed sediments were primarily clay and silt in water depths of approximately 5 m. Graphs provided by Yagi, Koiwa, and Miyazaki (1976) indicated that sediment resuspension was normally less than 100 mg/L; however, several readings exceeded 200 mg/L.

St. Johns River. In February 1982, a field study was conducted in the St. Johns River near Jacksonville, FL, to measure the sediment resuspension characteristics of a watertight bucket. Silty sediment, classified as

MH, was removed from Pier Basin 139 of the Jacksonville Naval Air Station to increase the depth in the basin to 4.5 m.

The watertight bucket consisted of a modified Yawn-Williams 13-cu yd clamshell bucket with side and top plates welded onto the top. The edge of each half was lined with rubber to ensure a watertight seal. A rectangular opening in the cover provided an opening for the pulley, and allowed air to escape during submersion.

The contractor estimated that the addition of the sides and top probably increased the bucket's capacity to about 15 cu yd (Hayes, Raymond, and McLellan 1984; McLellan et al. 1989).

Affected areas at two times background were 9.25, 0.47, and 24.8 acres for 50-, 75-, and 100-percent depths, respectively. Suspended solids concentrations at four times the background concentration affected an area of 2.0 acres at 100-percent depth. Background concentrations during the dredging operation ranged from 47 mg/L near the surface to 72 mg/L near the bottom. Concentration extremes associated with this test are summarized in Table 17.

Table 17
St. Johns River Watertight Bucket Field Test (McLellan et al. 1989)

Percent Depth	Suspended Solids (mg/L)	
	Maximum	Minimum
25	170	50
50	170	70
75	185	105
100	300	140

The watertight bucket reportedly spread resuspended sediment over a large area in the lower water column. This spread is possibly due to the displacement of the entrapped water within the bucket upon impact with the sediment. This could be prevented with the use of a cover that allows water to pass through the bucket during the descent, such as provided by the Japanese design. The watertight bucket reduced spillage during the ascent through the water column, thus reducing sediment resuspension in the middle and upper layers of the water column.

Durability of rubber gaskets as used on this watertight bucket could also be a problem in areas of stiff sediments or in debris-laden areas. Tongue-in-groove joints may be more effective for a wide range of conditions. Sediment resuspension data associated with an open bucket operating at this site can be found in Hayes, Raymond, and McLellan (1984) and McLellan et al. (1989).

Turbidity Barriers

Researchers in Australia and The Netherlands used turbidity barriers (Figure 15) to contain the sediment resuspended from a bucket dredge. Turbidity barriers are geotextile fabrics suspended from a metal framework down to a certain depth. The screen should be permeable with sufficiently fine mesh to restrict the movement of sediment particles. Considerable attention must be paid to the screen's movement, because careless handling of the screen could completely negate any advantage from its use (Pennekamp and Quaak 1990, Hoogerwerf 1990).

Sediment resuspension associated with turbidity barriers has been monitored at Hollandsche IJssel in The Netherlands and in Sydney Harbor, Australia. Descriptions of these field tests and the performance of turbidity barriers are given below.

Hollandsche IJssel. A comparison between a Japanese-built watertight bucket (3-cu m capacity) with turbidity barriers, an open bucket (2.5-cu m capacity) with turbidity barriers, and a Japanese watertight bucket (3-cu m capacity) without turbidity barriers was conducted in Hollandsche IJssel during May 1988.

The dredged material was primarily silt in water depths of 5 m. Suspended solid concentrations above background for the three dredges are provided in Table 18. The average background concentration at the test site was 35 mg/L (Pennekamp and Quaak 1990).

Sydney Harbor tunnel. In 1987, a bucket dredge removed sediment as part of the construction of a four-lane road tunnel under Sydney Harbor. An open bucket dredge with a turbidity barrier was used to dredge a portion of the tunnel. The turbidity barrier measured 25 by 20 m and consisted of tubular flotation chambers with weighted geotextile fabric extending to at least 2 m below the water. Dredging took place in water depths of 30 m.

The turbidity barrier reportedly reduced the surface turbidity considerably and proved effective in currents not exceeding 1 knot. In addition, the turbidity barrier withstood all waves generated by passing ferries (Hoogerwerf 1990).

Table 18
Hollandsche IJssel Turbidity Barrier Field Test (Pennekamp and Quaak 1990)

Dredge Type	Average Suspended Solids[1] (mg/L)
Watertight bucket with turbidity barrier	20
Conventional bucket with turbidity barrier	35
Watertight bucket without turbidity barrier	100

[1] Above background.

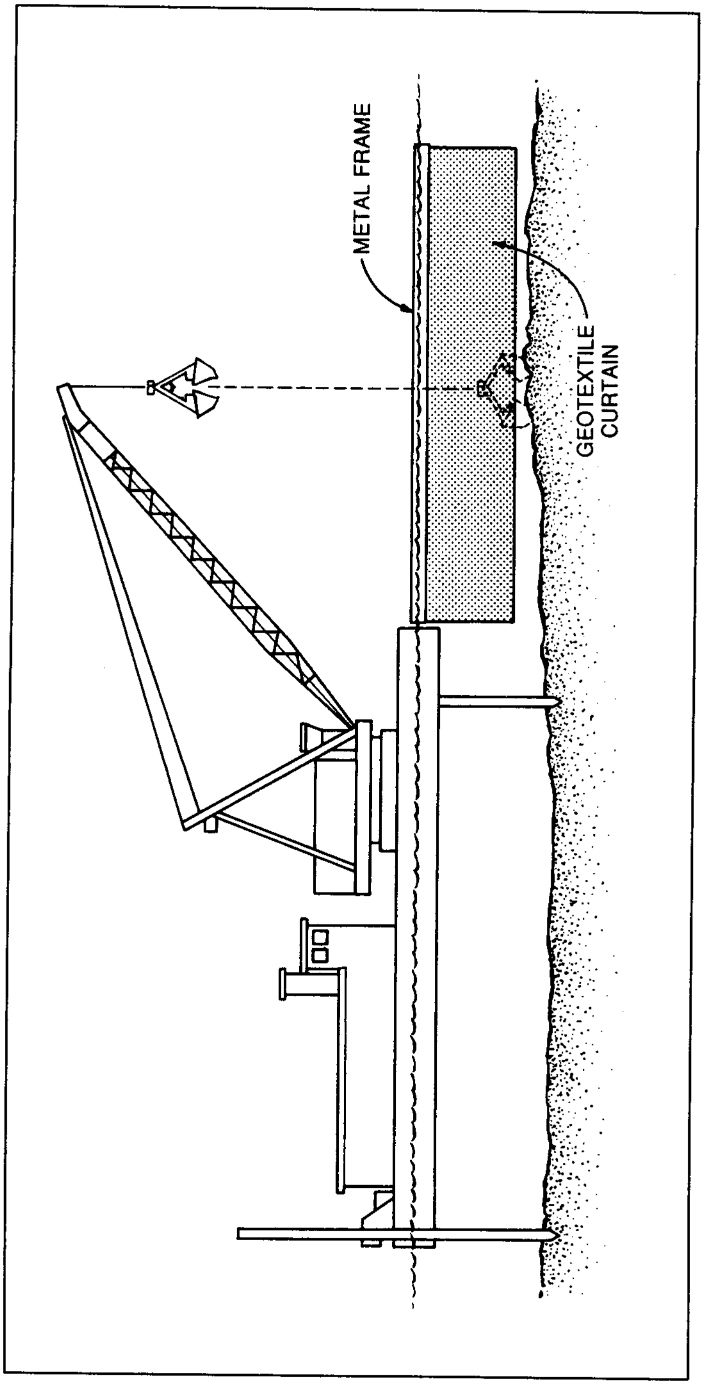

Figure 15. Turbidity barrier

5 Conclusions and Recommendations

Conclusions

Sediment contamination resulting from agricultural and industrial sources exists in many harbors, ports, and navigable streams. While no simple criteria exist regarding safe levels of sediment resuspension, less sediment resuspension reduces the potential for contaminant transport and subsequent release to the environment. This report summarized research efforts associated with developing innovative hydraulic, pneumatic, and mechanical technologies for dredging contaminated sediments.

Dredges that move sediment via hydraulic means routinely operate in almost every waterway in the United States and move millions of cubic yards of sediment each year. Commonly used hydraulic dredges include the cutterhead, modified dustpan, disc-bottom, bucket wheel, cutter suction, portable, and hopper dredges. Table 19 provides a summary of innovative hydraulic dredges.

Pneumatic dredges use natural and induced pressure differences rather than mechanical action to move sediment. The complete dredging process includes suction, discharge, and pressure-release steps. While some debate exists over the cost of pneumatic dredges, the generally passive nature of these dredges makes them a logical candidate for removing highly contaminated sediment. Table 20 provides a summary of innovative pneumatic dredges.

Clamshell or bucket, ladder, and dipper dredges are generally classified as mechanical dredges because they accomplish sediment removal and movement through entirely mechanically means. Ladder and dipper dredges have characteristically high sediment resuspension rates and would be unsuitable for dredging contaminated sediments. The bucket dredge is the most common mechanical dredge in the United States. Table 21 provides a summary of innovative bucket dredges.

Table 19
Summary of Innovative Hydraulic Dredges

Dredge Type	Major Features	Sediment Resuspension Test Sites
Clean-Up	Cutterhead Auger cutter Rectangular cover Sonar Grates	Unknown location in Japan
Matchbox	Cutterless Triangular cover Funnel intakes Angle control Vertical positioning Grates	First Petroleum Harbor Calumet Harbor New Bedford Harbor
Refresher	Cutterhead Helical cutter Cover Positioning equipment Check valves	T-Bay M-Bay
Modified Dustpan	Cutterless Curved plate Winglets Trailing plate	James River
Disc-Bottom	Cutterhead Cylinder cutter	None
Bucket Wheel	Cutterhead Wheel cutter Overlapping buckets	None
Cutter-Suction	Cutterhead Suction/cutter shaft	None
Portable	Delta Horizontal auger	New Bedford Harbor (horizontal auger)
Front-Open	Draghead Mixing blades Angle control Grates Density detectors Water jets	Chiba Port Nagoya Port Mikawa Port
IHC Roller Silt	Draghead Roller Adjustable inlet	Gray Harbor Pearl Harbor

Table 20
Summary of Innovative Pneumatic Dredges

Dredge Type	Major Features	Sediment Resuspension Test Sites
Pneuma	Three cylinders Distributor Air compressor Hole dredging attachments Trail dredging attachments Vacuum system Check valves	Duwamish Waterway Cape Fear River Aji River Chofu Port Kokura Port Gibraltar Lake
Oozer	Two cylinders Distributor Air compressor Vacuum system Cutters Covers Sonar	Osaka Bay
Airlift	Submerged recovery pipe Air compressor	None

Table 21
Summary of Innovative Mechanical Dredges

Dredge Type	Major Features	Sediment Resuspension Test Sites
Watertight bucket	Cover Sealed joints Exterior pulley	Aji River St. Johns River Hori River Oyabe River
Turbidity barrier	Floating frame Geotextile screens	Hollandsche IJssel Sydney Harbor Tunnel

Field tests of sediment resuspension characteristics have been conducted for most available dredge types and many modifications. However, a comprehensive comparison of the performance of various dredge types is difficult. Even if such a comparison were possible, the results would be largely inconsequential since site characteristics usually dictate the dredge type that must be used. Therefore, efforts should focus on improvement of the capabilities of each dredge type and on possible customization for certain conditions. In any case, the variability in sediment characteristics and testing conditions makes quantitative comparisons of the resuspension characteristics difficult; qualitative comparisons are most appropriate under as near-identical circumstances as possible.

In studies that have pitted various dredges operating under near-identical conditions, conventional dredges have proven to be surprisingly successful (Hayes, McLellan, and Truitt 1988; Otis, Andon, and Bellmer 1990). However, this does not negate the need for pursuing equipment innovations to improve current dredging operations. Also, evaluating the effectiveness of any cleanup alternative must consider other existing sources of sediment spread, such as storm surges and boat traffic.

Countries outside of the United States have done more to advance the development and testing of innovative dredging technologies. The US dredging industry could contribute more to the development of this equipment if added incentives are provided. The development of such equipment must continue, as contaminated ports and harbors around the country that require environmentally driven restrictions are dredged. Additionally, the import restrictions of the Jones Act have prevented innovative designs from being brought to the United States.

Recommendations

The innovative designs and operations discussed in this paper show promise for future dredging applications. Unfortunately, the details of overseas data collection efforts and raw data are not easily accessible to evaluate the effectiveness of these innovations. Valuable information could be gained through the exchange of test results, observation of the equipment in operation, and equipment testing.

Direct observation of these innovations is recommended to better understand their benefits. In addition, more field tests in the United States are needed to provide detailed information on the sediment resuspension characteristics of these innovations. Field tests would also be useful in determining the suitability of various innovative dredges for removing contaminated sediment. Furthermore, proper operator training would ensure that the dredges are operated as effectively as possible to minimize sediment resuspension. Better incentives are needed to encourage US dredging companies to develop dredges and operating procedures that will minimize sediment resuspension.

References

Barnard, William D. 1978. Prediction and control of dredged material dispersion around dredging and open-water pipeline disposal operations. Contract Report DS-78-13. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Case, Nancy L., Woolley, Cal, and Perkins, Steve. 1984. Draghead designs versus production (dredge *Essayons* Testing, 1983-1984). In *Proceedings, conference dredging '84*. Vol 1. New York: ASCE Waterways, Port, Coastal and Ocean Division.

City of Santa Barbara, CA, Public Works Department, Water Resources Division. 1987 (May). Gibraltar Lake restoration project. US Environmental Protection Agency Clean Lakes Program.

Courtney, William J. 1986. The capability of the Pneuma pump for continuous high solids transport. In *Proceedings, 19th dredging seminar*. College Station, TX: Texas A&M University.

Cullinane, M. John, Averett, Daniel E., Shafer, Richard A., Male, James W., Truitt, Clifford L., and Bradbury, Mark R. 1986. Guidelines for selecting control and treatment options for contaminated dredged materials requiring restrictions. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

d'Angremond, Kees, de Jong, Andries J., and de Waard, Cornelis P. 1984. Dredging of polluted sediment in the First Petroleum Harbor, Rotterdam. In *Third United States-The Netherlands meeting on dredging and related technology*. 169-190. Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Faldi, Giovanni. 1990. A transportable Pneuma dredger for polluted bottoms. Firenze, Italy: The Dock and Harbour Authority, Pneuma S.R.L.

Fujii, K., and Otsu, F. 1987. Removal work of organic deposit by Oozer pump dredge. In *Proceedings, 12th US/Japan experts meeting on management of bottom sediments containing toxic substances*. Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Goodier, J. Leslie. 1981. Dredging systems for environmental improvement. *International Dredging Review:* 12-17.

Hamasuna, J. 1990. Example of latest techniques for bottom sludge dredging. In *Proceedings, 14th US/Japan experts meeting on management of bottom sediments containing toxic substances.* Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Havis, Robert N. 1988. Sediment resuspension by selected dredges. *Environmental Effects of Dredging Technical Note* EEDP-09-2. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Hayes, Donald F. 1986. Guide to selecting a dredge for minimizing resuspension of sediment. *Environmental Effects of Dredging Technical Note* EEDP-09-1. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Hayes, D. F., Raymond, Gene L., and McLellan, T. N. 1984. Sediment resuspension from dredging activities. In *Proceedings, conference dredging '84.* Vol 1. New York, NY: ASCE Waterways, Port, Coastal and Ocean Division.

Hayes, Donald F., McLellan, T. Neil, and Truitt, Clifford L. 1988. Demonstrations of innovative and conventional dredging equipment at Calumet Harbor, Illinois. Miscellaneous Paper EL-88-1. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Herbich, John B., and Brahme, Shashikant B. 1991. Literature review and technical evaluation of sediment resuspension during dredging. Contract Report HL-91-1. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Hoogerwerf, F. W. 1990. Dredging works for the Sydney Harbour Tunnel. *Terra and Aqua* 42:21-26.

Hudson, R. E., and Vann, R. G. 1984. An overview of a dredging demonstration in contaminated material, James River, Virginia. In *Proceedings, 8th US/Japan experts meeting on management of bottom sediments containing toxic substances.* 312-325. Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Huston, J. W., and Huston, W. C. 1976. Techniques for reducing turbidity associated with present dredging procedures and operations. Contract Report D-76-4. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Irie, Yoshitugu. 1984. Field dredging test of soft mud layer by a front-open type drag head. *Proceedings, 8th US/Japan experts meeting on management of bottom sediments containing toxic substances.* 326-380. Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Kaneko, A., and Watari, Y. 1983. Dredgers for fighting pollution. *Dock and Harbour Authority* 64(752):53-57.

Kaneko, Akihiro, Watari, Yoshiharu, and Aritomi, Noriyoshi. 1984. Specialized dredges designed for bottom sediment dredging. In *Proceedings, 8th US/Japan experts meeting on management of bottom sediments containing toxic substances.* 450-476. Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Kasajima, Shiro. 1984. Removal of bottom sediments in Osaka Port by the Pneuma pump dredge *Shunkai.* In *Proceedings, 8th US/Japan experts meeting on management of bottom sediments containing toxic substances.* 16-39. Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Koba, Hiromi, and Shiba, Toyoaki. 1983. Test dredging of bottom sediments in Osaka Bay. In *Proceedings, 7th US/Japan experts meeting on management of bottom sediments containing toxic substances.* 225-251. Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

McLellan, T. N., Truitt, C. L., and Palermo, M. R. 1986. Evaluation of the Matchbox dredgehead and submerged diffuser. In *Proceedings, 19th dredging seminar.* College Station, TX: Texas A&M University.

McLellan, T. N., Havis, R. N., Hayes, Donald F., and Raymond, Gene L. 1989. Field studies of sediment resuspension characteristics of selected dredges. Technical Report HL-89-9. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Mitre Corporation (McLean, VA). 1983 (May). Implementation of innovative dredging techniques in the Chesapeake Bay region. Annapolis, MD: US Environmental Protection Agency.

Nishi, Kasuyoshi. 1976. Dredging of high-density sludge using Oozer pump. In *Proceedings, WODCON VII.* San Francisco, CA: World Organization of Dredging Associations.

Okayama, Y. 1983. Effective removal of soft mud by front-open type draghead. In *World dredging congress 1983.*

Otis, Mark J. 1990. A pilot study of dredging and disposal alternatives for the New Bedford Harbor, Massachusetts, Superfund site. In *Proceedings, 14th US/Japan experts meeting on management of bottom sediments containing toxic substances.* Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Otis, Mark J., Andon, Steve, and Bellmer, Russell. 1990. New Bedford Harbor Superfund pilot study: Evaluation of dredging and dredged materials disposal. Waltham, MA: USAE Division, New England.

Palermo, M. R., and Randall, R. E. 1990. Practices and problems associated with economic loading and overflow of dredge hoppers and scows. Technical Report DRP-90-1. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Palermo, M. R., et al. 1989. Evaluation of dredged material disposal alternatives for US Navy Homeport at Everett, Washington. Technical Report EL-89-1. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Pennekamp, J. G. S., and Quaak, M. P. 1990. Impact on the environment of turbidity caused by dredging. *Terra and Aqua* 42.

Pneuma S. R. L. Undated. Pneuma system. Firenze, Italy.

Raymond, G. L. 1984. Techniques to reduce the sediment resuspension caused by dredging. Miscellaneous Paper HL-84-3. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Richardson, T. W. 1984. Performance tests of Pneuma dredge pump. In *Proceedings, 8th US/Japan experts meeting on management of bottom sediments containing toxic substances*. 419-433. Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Richardson, Thomas W., Hite, John E., Shafer, Richard A., and Ethridge, James D. 1982. Pumping performance and turbidity generation of model 600/100 Pneuma pump. Technical Report HL-82-8. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Sato, Eisuke. 1976. Application of dredging techniques for environmental problems--Dredging methods for bottom sediments without polluting water. In *Proceedings, WODCON VII*. San Francisco, CA: World Organization of Dredging Associations.

Sato, Eisuke. 1984. Bottom sediment dredge "Clean-Up" - Principle and results. In *8th US/Japan experts meeting on management of bottom sediments containing toxic substances*. 403-418. Fort Belvoir, VA: US Army Engineer Water Resources Support Center.

Sorensen, Alf H. 1984. Development of the dredging wheel. In *Proceedings, conference dredging '84*. Vol 1. New York: ASCE Waterways, Port, Coastal and Ocean Division.

Toyo Construction Company, Ltd. Undated. Oozer pump dredge - *Taian Maru*. Tokyo, Japan.

Toyo Construction Company, Ltd. 1978 (Jan). Comment on dredging technology for muddy sediments. Tokyo, Japan.

US Army Corps of Engineers. 1983. Dredging and dredged material disposal. Engineer Manual 1110-2-5025. Washington, DC.

US Army Engineer District, Norfolk. 1982. James River demonstration project; Final report. Norfolk, VA.

US Army Engineer District, Seattle. 1976. PCB cleanup operations, Duwamish Waterway, Seattle Harbor, Washington. Seattle, WA.

Van Dooremalen, J. J. C. M., Barneveld-Binkhuysen, J. P. F., Loevendie, R. H., and Verboom, P. 1983. Dragheads: from the early beginning to the latest developments. In *Proceedings, WODCON X*. Singapore: World Organization of Dredging Associations.

Van Raalte, G. H., and Zwartbol, A. 1986. The disc-bottom cutterhead: A Report on laboratory and field tests. In *Proceedings, XIth world dredging congress*. Brighton, UK: World Organization of Dredging Associations.

Yagi, Tokuji, Koiwa, Taisei, and Miyazaki, Shyoji. 1976. Turbidity caused by dredging. In *Proceedings, WODCON VII*. San Francisco, CA: World Organization of Dredging Associations.